Plate 1. Frontispiece.

The Chilton Valley from the slopes of Sugarloa

MASS MOVEMENT IN THE CHILTON VALLEY

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the University of Canterbury
in partial fulfilment of the
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Geography

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ABSTRACT

Slow mass movement processes in the Chilton Valley (South Island High Country) were measured using different techniques. Analysis of this data showed a rate of soil creep slightly greater than that measured in other humid temperate areas and much smaller than rates measured in sub-arctic and some semi-arid regions. Both vegetation and angle of slope affected the measured rates. The main cause of soil creep was shown to be freezing and thawing of the soil moisture. Movement of scree surface material was comparable to rates measured in most other studies of this process. Freezing and thawing of the interstitial moisture also caused most of this type of movement. Comparison of these rates with those of other processes (measured by other workers in this area) showed that slow mass movement processes contributed only a small amount to total erosion and transportation compared with debris flows. Slope wash was shown to be more important than soil creep but less important than talus creep. The total rate of deposition since deglaciation of this area (derived from the volume of the alluvial fan at the bottom of the valley) was shown to be much larger than the rates of measured processes.

CHAPTER 1 INTRODUCTION

AIMS

Beginning with the comprehensive studies of Jackli (1957) and Rapp (1960a), an important emphasis in recent work on the development of slopes has been placed on the measurement of contemporary processes and the relation of these to existing forms. This approach does not rule out the importance of past processes but rather attempts to understand present processes, so that more light can be cast on past processes. Leopold, Wolman & Miller (1964, p.7) have observed that the gap between our understanding of specific processes in microcosm and the explanation of major large-scale landforms is still wide. This is certainly true of the South Island High Country for which the knowledge of the quantitative amounts of erosion caused by different processes is very limited. The causes of slow mass movement in this area are also not well understood.

Consequently the main aims in this study of slow mass movement processes in the Chilton Valley are:

(1) to measure the rates of slow mass movement processes in the South Island High Country and to compare these rates with those of other processes.

(2) to investigate the causes of slow mass movement processes in this environment and to relate these findings to theories concerning these processes.

(3) to consider these processes in relation to specific landforms in the general context of slope development.

Ideally, a study of erosional processes should include as many processes as possible and should extend over a period which allows the average rate to be accurately fixed. This study is, therefore, somewhat limited by its concentration on one small group of processes and by the short period of investigation. However, previous work on other groups of contemporary processes in this area by Brundall (1966) and Soons (1966) may lessen the first of these limitations.

PREVIOUS WORK

The most important investigations of mass movement are summarized in Table 1. The majority of these investigations have been made within the last 20 years. Many were carried out in arctic or sub-arctic areas, where there was an early emphasis, since the effects of rapid movements are obvious and rates more easily assessed. However, studies of soil creep and scree movement have also been made under conditions more similar to those of the present study. The action of freezing and thawing of soil moisture in causing creep and scree movement has been examined by Schmid (1955, in Young 1958), Gradwell (1957) and Caine (1963). In humid temperate regions soil creep (caused by soil moisture changes) has been measured by Young (1958, 1960 and 1963) and Kirkby (1965). Similar studies have been made in semi-arid areas by Schumm (1956 and 1964), Emmett (1965), and Leopold, Emmett & Myrick (1966).

The amount of work done in this and related fields in the South Island High Country is very limited. Zotov (1939) and Cumberland (1944, p.68) discussed, in general terms, the extent

Table 1

Work Done in the Field of Mass Movement Investigation

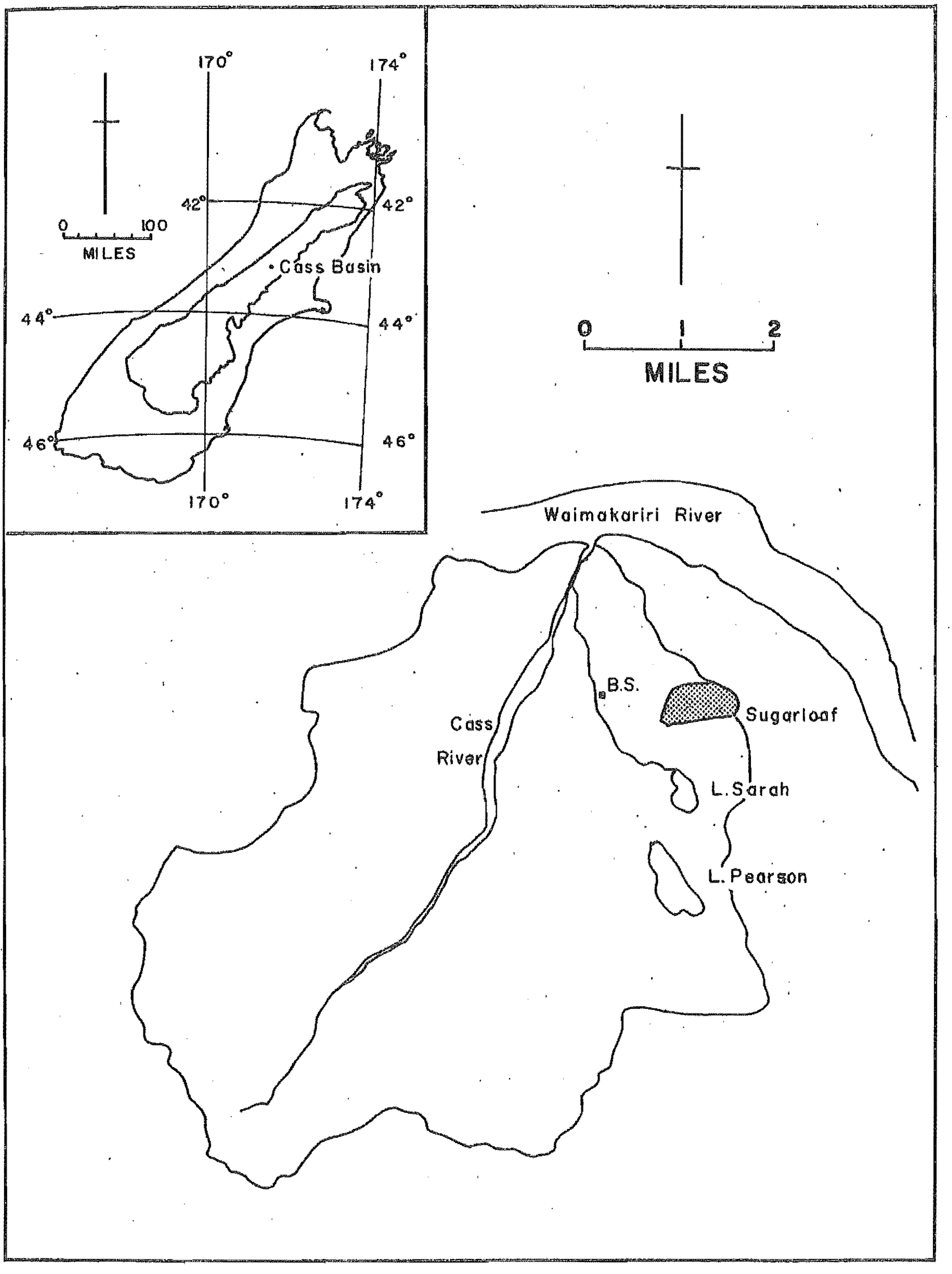
Author	Study Area	Period of Study	Process
Arctic or sub-arctic			
Williams (1957)	Norway	-	Solifluction
Jahn (1960)	Spitsbergen	2 yrs	Soil wash and solifluction
Rapp (1960a)	N. Sweden	8 yrs	All mass movements
____ (1960b)	Spitsbergen	4 weeks	Rockfall and talus development
Washburn (1962)	Alaska	-	Solifluction and soil creep
Everett (1961)	N.W. Alaska	-	Solifluction and soil creep
Temperate areas (upland)			
Fisher (1952)	Cass Basin		Scree movement
Gradwell (1954)	Molesworth (S.I.H.C.)	24 days	Soil frost action
________ (1957)	Molesworth (S.I.H.C)	2 yrs	Scree movement
________ (1960)	Fox's Peak (S.I.H.C.)	3 yrs	Soil frost action
Schmid (1955)	Rhine-Main	-	Soil frost action
Caine (1963)	Lake District	8 mnths	Soil creep and scree movement by frost action
Temperate areas (lowland)			
Young (1958)	England	3½ yrs	Soil creep and soil wash
______ (1960)	England	2 yrs	Soil creep
______ (1963)	England	4 yrs	Soil creep
Arid and semi-arid areas			
Schumm (1956)	S. Dakota	2½ yrs	Soil creep and slope wash
______ (1964)	W. Colorado	4 yrs	Soil creep and slope wash
Emmett (1965)	U.S.A.	5 yrs	Soil creep and slope wash
Leopold, Emmett, & Myrick (1966)	N. Mexico	5 yrs	Soil creep and slope wash

and types of erosion in this area with particular reference to accelerated erosion. Gibbs & Raeside (1944) mapped the severity of erosion and also discussed the types of erosion on different soils. The only measurements of slow mass movement processes in this region have been made by Gradwell (1957), though Fisher (1952) has observed the movement of marked stones and suggested some causes. No measurements of subsurface movement have been published. Important work has been carried out in related fields, particularly since the Tussock Grasslands Research Committee Report (1954). Of relevance to the present enquiry are McArthur's work on the geomorphology of the Cass Basin (1964), Gillingham's study of infiltration at Porters Pass (1964), Brundall's thesis on the debris flows around Cass (1966), and the investigation of run-off in the Chilton Valley by Soons (1966). Most of the other work in related fields has been summarized by Hayward (1967).

DESCRIPTION OF THE AREA

The Chilton Valley was chosen by J.N. Rayner as typical of the drier eastern parts of the Southern Alps. The location of the Chilton Valley is shown in Figure 1. The geology, soils, climate, and vegetation of the Cass Basin have been described by McArthur (1964), while the Chilton Valley itself has been described by Soons & Rayner (In Press). A long period of rainfall records at the Biological Station (Figure 1), shows that the annual average is 52 inches. Temperature records have been kept for four years and show absolute ranges of 29°F to 93°F (-2°C to 34°C) in summer and 9°F to 58°F (-13°C to 14°C) in winter. Soils are of the Kaikoura series and have been described along with

Figure 1. Location of Study area.
The main map shows the boundary of the Cass Basin with the Chilton Valley shaded. The inset shows the location of the Cass Basin within the South Island High Country (Gibbs & Raeside, 1944).



170°
174°
42°
42°
0
100
MILES
Cass Basin
44°
44°
46°
46°
170°
174°
0
1
2
MILES
Waimakariri River
B.S.
Sugarloaf
Cass
River
L. Sarah
L. Pearson

other greywacke-derived soils by McDonald (1961).

The valley has a considerable range of slopes and aspects. Figure 2 shows the distribution of slopes within the valley while Figure 3 summarizes the slopes in terms of orientation and inclination. The diagram shows a pole facing south-west at between 10° and 20° (the valley bottom), and two secondary maxima oriented north-west and south-east at higher angles (the valley sides). Most slopes, especially those facing the north-west are mantled by periglacial screes of unknown depth (Soons & Rayner, In Press).

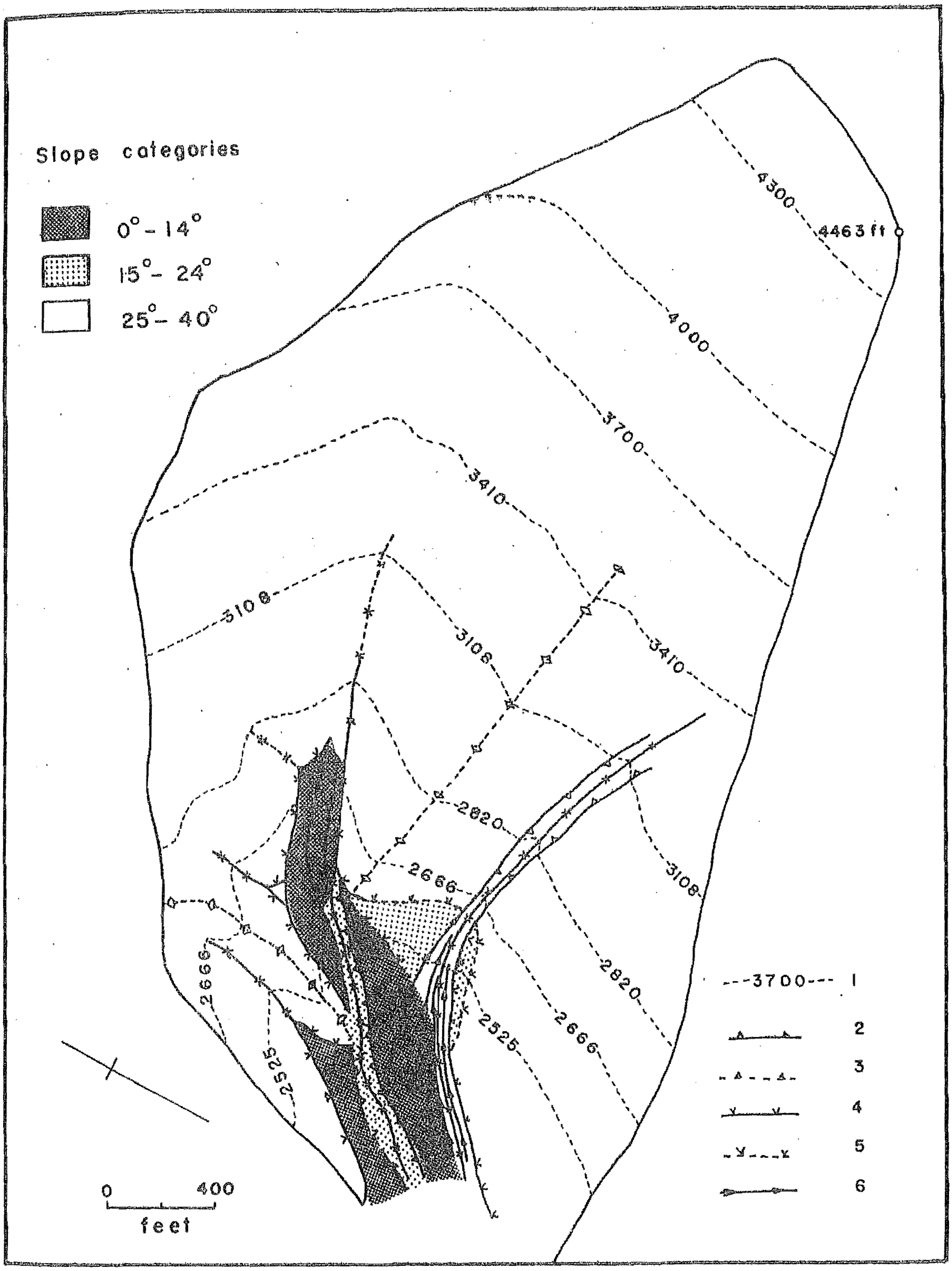
Vegetation is noticeably affected by aspect (Figure 4). From the top of Sugarloaf to the valley mouth the cover of the north-west facing slopes changes from extensive areas with little vegetation, to a large area of manuka (Leptospermum scoparium) with a few scattered beech trees (Nothofagus solandri var. cliffortioides), and randomly scattered patches of bare scree, and finally to an area with cassinia (Cassinia fulvida) and matagouri (Discaria toumatou) and a ground cover of hard and silver tussock (Festuca novae-zelandiae and Poa caespitosa). The valley floor is covered mainly by tussock but also has some cassinia and matagouri especially on old debris flows. The south and south-east facing slopes are characterized by the presence of celmisia (Celmisia spectabilis). Tussock and matagouri are also present as are some other varieties of low scrub particularly Inaka (Dracophyllum uniflorum), snow totara (Podicarpus nivalis) and Hebe (Hebe buxifolia).

Haven't been called this for 10 years,
now H. odora

Figure 2. Geomorphic map of the Chilton Valley.

1. Contours in feet
2. Convex break of slope
3. Convex change of slope
4. Concave break of slope
5. Concave change of slope
6. Old mudflow levee

Source: Soons & Rayner, In press.



Slope categories
0° - 14°
15° - 24°
25° - 40°
4300
4463 ft
4000
3700
3410
3108
3108
3410
2820
2666
3108
2820
2666
2525
2666
2525
3700 1
2
3
4
5
6
0 400
feet

Figure 3. Orientation and inclination of Chilton Valley slopes. Constructed from the orientation and inclination at fifty randomly chosen points. The arrow shows the direction of the axis of the valley.

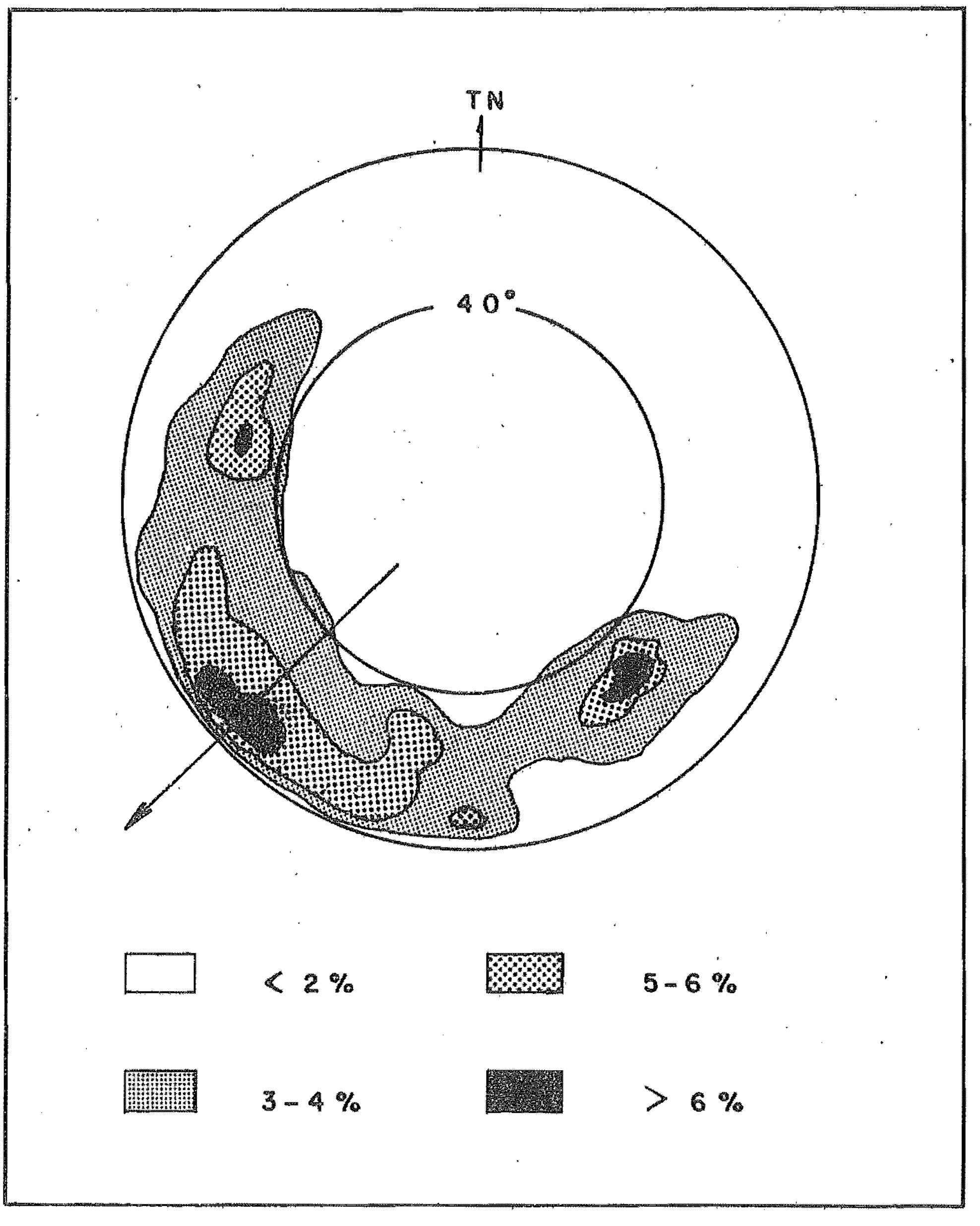
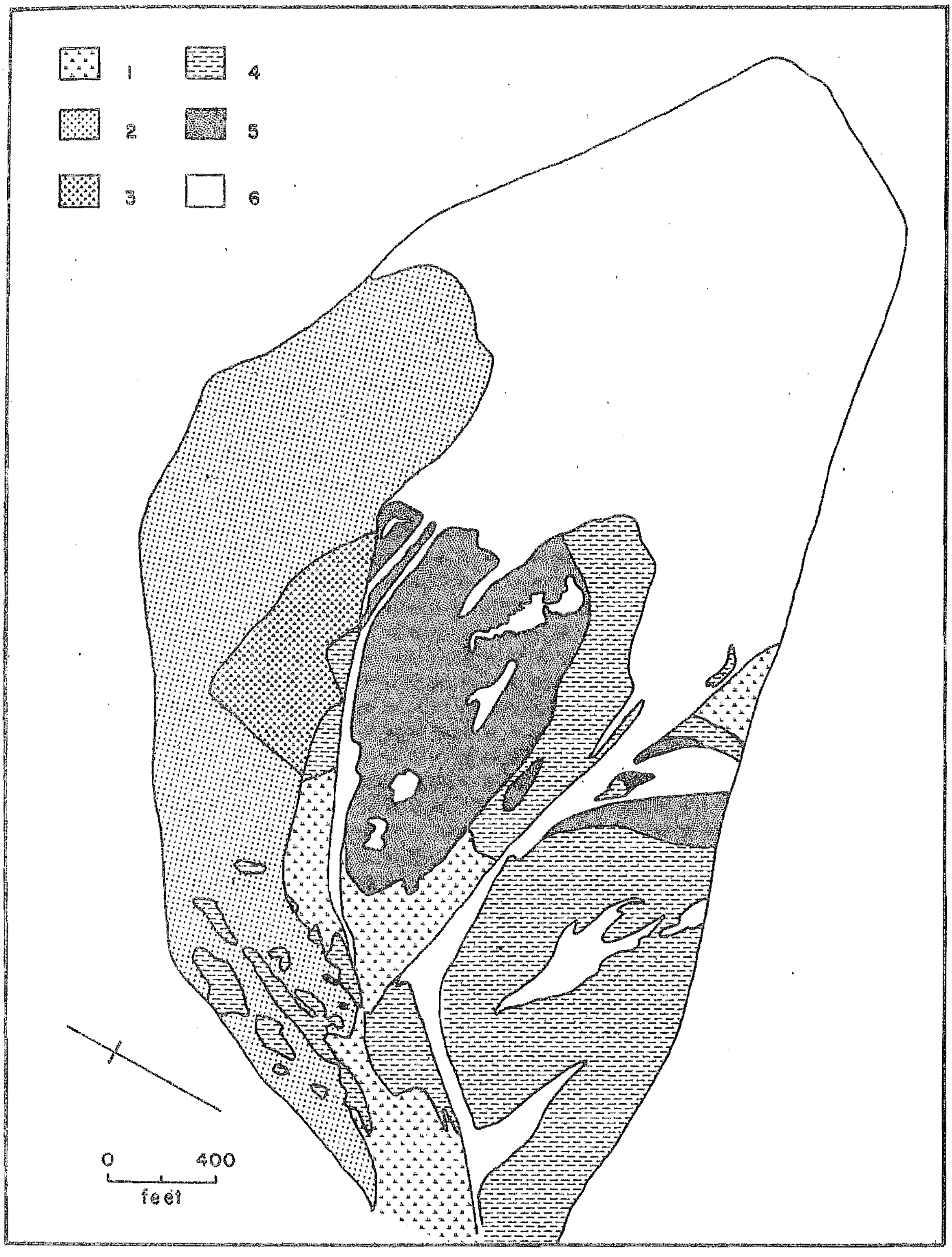

TN
40°
< 2 %
5-6 %
3-4 %
> 6 %

Figure 4. Vegetation Map of the Chilton Valley.

1. Tussock with low scrub
2. Short tussock with celmisia and low scrub
3. Tussock with hebe and dracophyllum
4. Cassinia and matagouri scrub with tussock
5. Manuka scrub and bare earth
6. Bare earth, scree, with occasional vegetation

Source: Soons & Rayner, In press.


1
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400
feet

CHAPTER 2 METHODS AND MATERIALS

In this study there was a strong emphasis on field measurement as a source of data. The methods used to measure mass movement and related features, and those used in laboratory and statistical analysis are discussed in this chapter.

METHODS OF DATA COLLECTION

Many different methods have been used to collect information on slow mass movement processes. Some of these are discussed by Selby (1966). While successful methods of measuring surface movement (such as recording the position of marked stones with respect to a reference point) have been in use for almost 20 years, measurement below the surface still presents many problems. Most of the attempts to measure subsurface movement are summarized in Table 2.

The type of device used is governed by the needs of the study. If an overall rate of soil movement is required, markers can be inserted and then traced at a much later date, but if causes are being investigated by correlating short term variations in movement with climatic or other variations, then it is necessary to make frequent recordings of subsurface movement without disturbing the soil. On this basis two types of movement can be distinguished:

(1) Long period measurement

(2) Short period measurement.

Long Period Measurement

The following methods were employed in this study.

Table 2

Attempts to Measure Subsurface Movement

Author	Measuring Device	Processes
Short term changes		
Williams (1957 and 1962)	PVC tube with strain gauges on probe.	Solifluction
Kirkby (1967)	T-bars	Soil creep
Cassidy (In Kirkby 1965)	Inclinometer with $1\frac{1}{4}$" tube	--
Everett (1966)	Linear motion transducers	Soil creep and solifluction
Long term measurements		
Young (1960)	Young pit	Soil creep
Caine (1963)	PVC tubing	Soil creep
Schumm (1964)	Buried beads and dowels	Soil creep
Kirkby (1965)	Young pit	Soil creep
Cassidy (In Kirkby 1965)	PVC tubing with quick-setting cement	--
Emmett (1965)	Young pit with vertical pieces of aluminium for markers	Soil creep

Young Pits. These have been described by Young (1960 and 1963), Kirkby (1965) and Selby (1966). In this study the position of the markers in the side of the pit was related to two reference points in the bottom of the pit, near the upslope and downslope edges (Figure 6), and the horizontal distance of the markers from a vertical line above the bottom marker was also measured. The markers used were six inch long nails. While very accurate measurements may be made by use of the Young Pit, there is a possibility that soil disturbance may effect soil moisture conditions and lateral movement, towards the replaced but uncompacted soil, may occur. Emmett (1965) also suggests that soil may move around the type of markers used by Young and Kirkby and also in this study.

Surely the P.V.C should have had a stopper on the end?

PVC Tubing. Two types of PVC tubing, with outside diameters of ¾ inch and ¼ inch, were used. The ¾ inch tubing was inserted in vertical auger holes. As the original curvature of the tubing was placed concave upslope, any displacement downslope of the vertical could be considered to represent slope movement. The ¼ inch tubing was inserted by driving a hole with a ¼ inch x ¼ inch bar of steel, threading the tube onto a length of No. 8 gauge wire, inserting this in the hole and removing the wire. At the end of the period the position of the tubes was traced, after carefully excavating a hole alongside each tube.

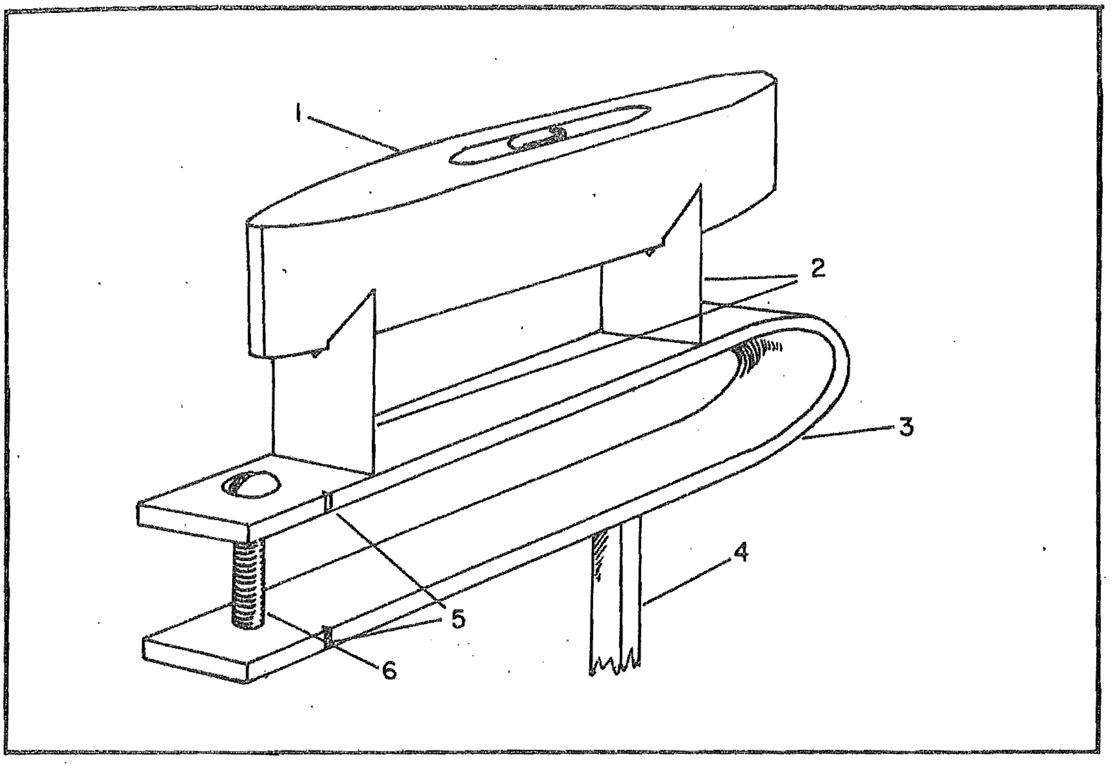
Columns of Stones. Columns of marked stones were inserted in auger holes near the sites of ¾ inch PVC tubing. The main function of these columns was to indicate any shearing of the surface layers which the PVC tubing might not have reflected.

Figure 5. Sketch of a T-bar

1. Spirit level
2. V-shaped brass holders
3. 1" x $\frac{1}{8}$" steel
4. $\frac{1}{4}$" x $\frac{1}{4}$" steel
5. Measurement nicks
6. Brass adjusting bolt.

Figure 6. Cross-section of a Young Pit

1. Plumb line
2. 6" nails
3. Reference pins.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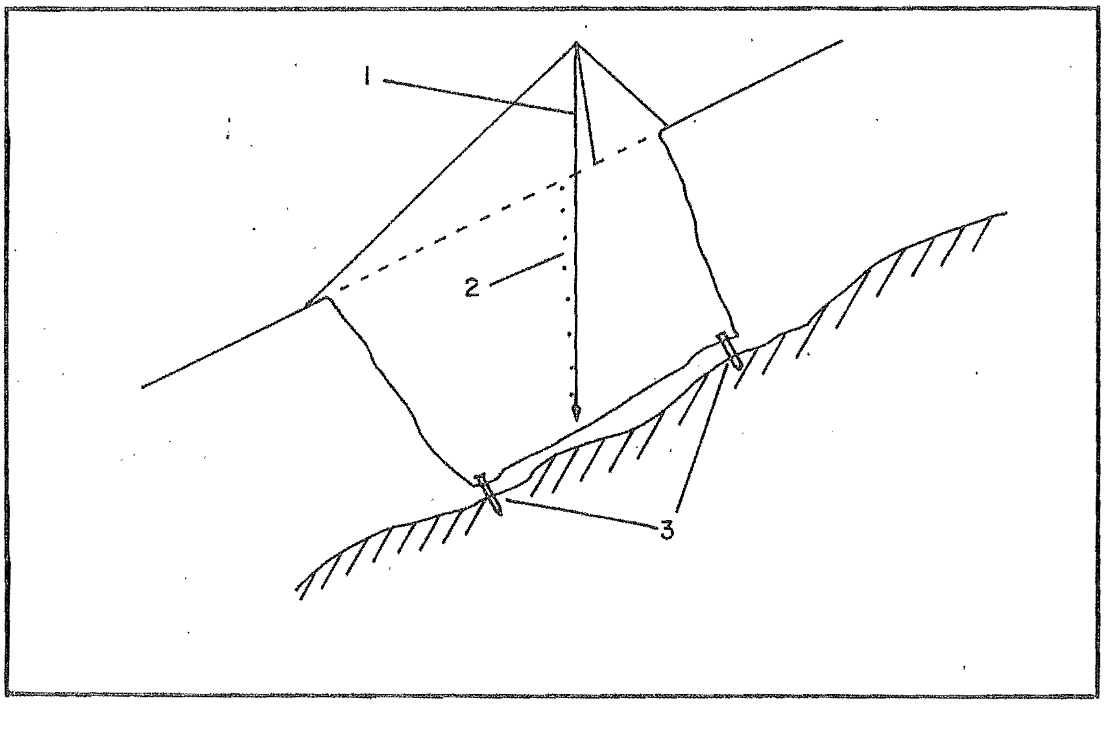

1
2
3

They were traced in the same way as the PVC tubing. Results given by this method were not considered as accurate as the ¼ inch PVC tubing results since it could not be guaranteed that the marked stones were placed in a vertical column.

T-Bars. These gave some indication of relative amounts of movement but no quantitative results regarding the rates of soil creep were obtained. T-bars are discussed more fully in the next section.

Short Period Measurement

Marked Stones. Measurement of surface movement was made by recording the distance between the upslope edge of painted stones and a line stretched between two reference points. These reference points were rods driven deeply into the ground. A check on their position with respect to more stable points (such as a rod buried at the crest of a ridge or a mark on a large rock), which were assumed not to move, was made at the beginning and end of the period. Because of the blocky surface the accuracy of the measurements was probably about ± 5 mm (due to parallax error).

T-Bars. This device was similar to that used by Kirkby (1965) and described by Chorley & Slaymaker (1964). The instrument is shown in Figure 5. To ensure that the level was placed in the same position for each measurement it was nicked so that it only fitted onto the V-shaped brass holders in the one position and so that it could face one direction only. Changes in the tilt of the T-bar were then measured in the following ways: the level was placed in position, the bubble centred by adjustment of the brass bolt, and the distance between the jaws at a marked point measured to 0.01 cm with vernier calipers. The difference between this measurement and the preceding one was then converted by trigonometry into the change of tilt of the vertical bar. By these means an accuracy of ± 2 minutes was attained and this often enabled movement over a period of 24 hours to be discerned. However, T-bars were also very susceptible to disturbance. Since sheep were sometimes observed within the valley it is likely that they were responsible for disturbing the instruments. When a large movement was measured and thought to be due to such disturbance, it was ignored. T-bars were also found to be more suited to fine cohesive soils than to scree slopes where it was often difficult to establish the instruments in a stable position.

The T-bar results were expressed in terms of average angular shear integrated over the length of the vertical bar. To enable comparison of movement in soil layers of different thicknesses, five different lengths of bar, 60, 50, 35, 25, and 20 cm. were used. Kirkby (1965) has shown that because the vertical bar is rigid, the T-bar shows only one-fifth of the actual magnitude of movement. Assuming that this factor is constant, tilts for different periods can still be compared and the use of the T-bar in investigating causes of soil movement is not invalidated.

<u>Inclinometer</u>. An attempt to measure the change in position of the ¾ inch PVC tubing was made using an inclinometer consisting of a weighted needle and a small brass protractor calibrated at 5° intervals. The needle could be locked by the cable release

(on which it was lowered into the tube) so that the recorded angle for any specified depth could be read on removing the instrument. Measurements were made for three or four depths in each tube. The accuracy of the inclinometer was rather doubtful, for although the position of the needle could be read to $\pm 2^{o}$, there was no way of ascertaining that this inclination was in the direction of maximum surface slope. Consequently three readings were taken at each depth and the mean value used. These readings can only be considered accurate to $\pm 5^{o}$. Since 44 tubes, each involving three or four readings, were used in the enquiry, a great deal of time was used for doubtful returns.

Location of Sites

In establishing the sites at which measurement of mass movement was made, it was recognised that a small area could contain a wide range of influences on soil movement and that its occurrence might be locally quite variable. Consequently the main considerations were the need for detailed information and, balanced against this, the need to represent different vegetation, aspect, and slope conditions. With this in mind the four experimental areas shown in Figure 7 were chosen. Sites 1 and 2 were on the south-east facing slopes dominated by celmisia, tussock, and low scrub, but while Site 1 contained isolated hummocks of tussock and celmisia (Plate 2), Site 2 was almost completely vegetated (Plate 3). Site 3 was a completely unvegetated patch among the manuka on the north-west facing slopes (Plates 4 and 5). Site 4 was on the more gently sloping valley floor, with a vegetation cover of tussock and low scrub (Plate 6).

Figure 7. Location of sites

1. ¼ inch PVC tube - traced

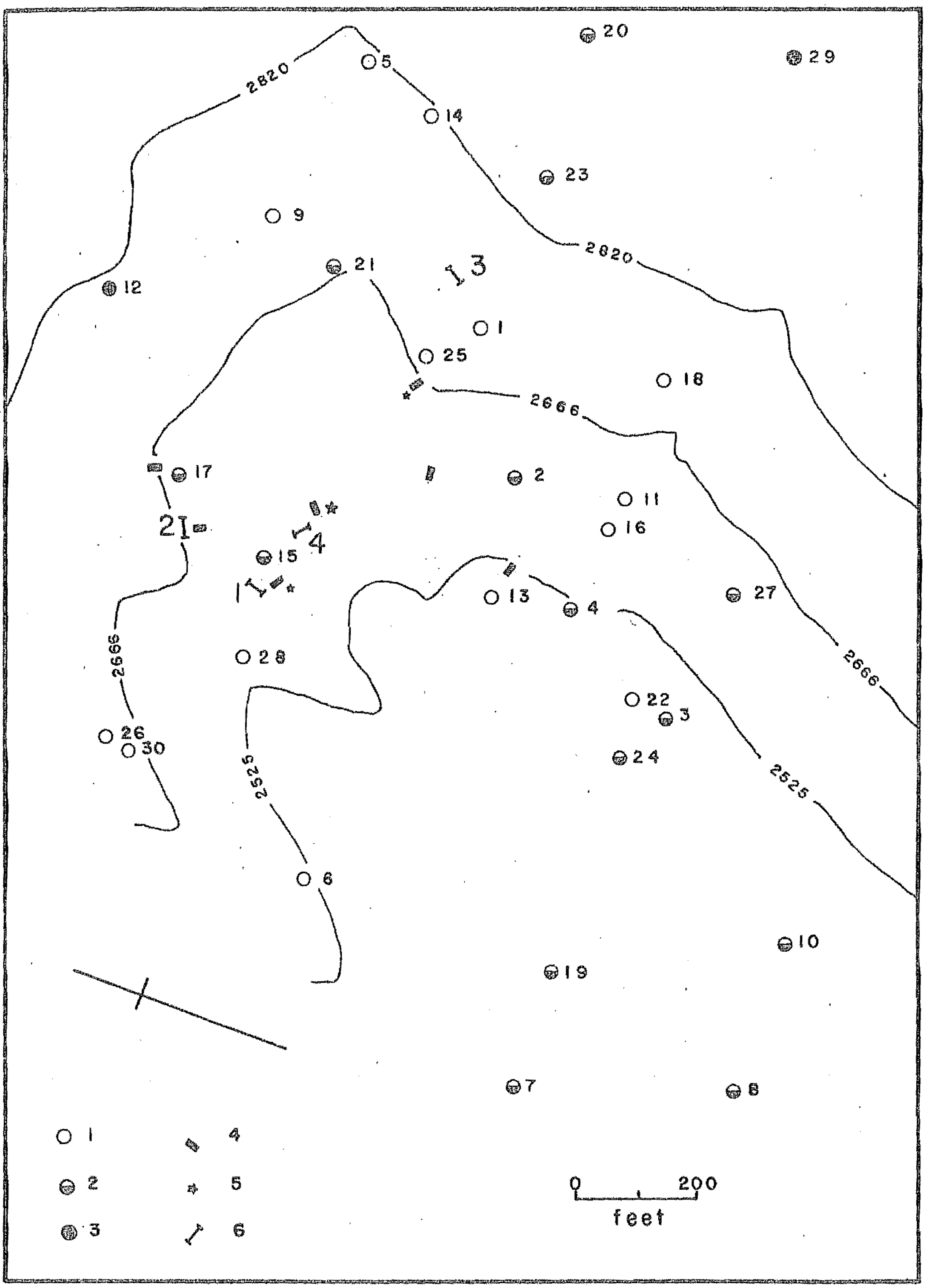
2. ¼ inch PVC tube - removed by animals or birds

3. ¼ inch PVC tube - not relocated

4. run-off plot

5. climate plot

6. main mass movement site



2820
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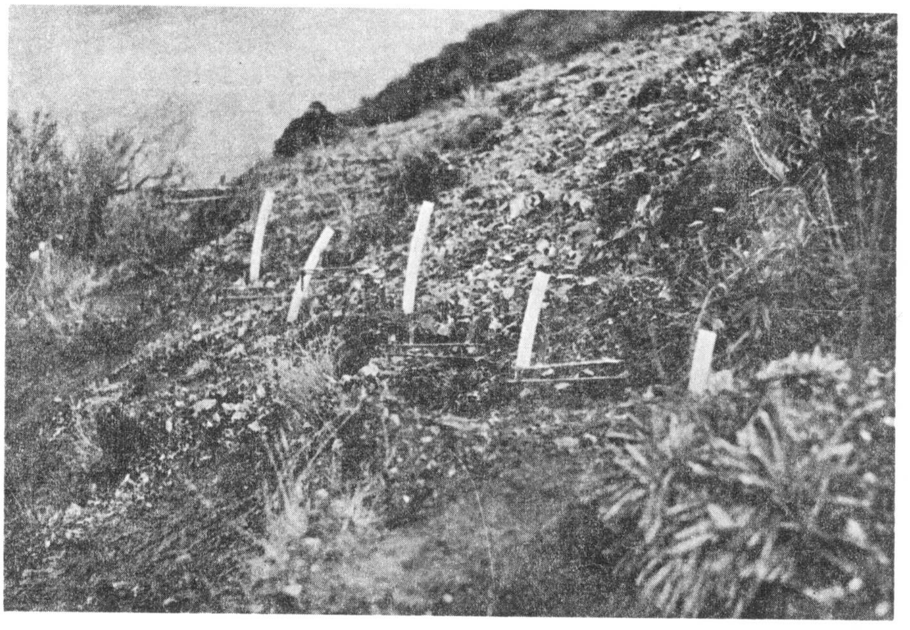
200
feet

Plate 2. Surface characteristics at Site 1.

Plate 3. Site 2. Note the complete vegetation cover consisting of celmisis, tussock, and some low scrub.



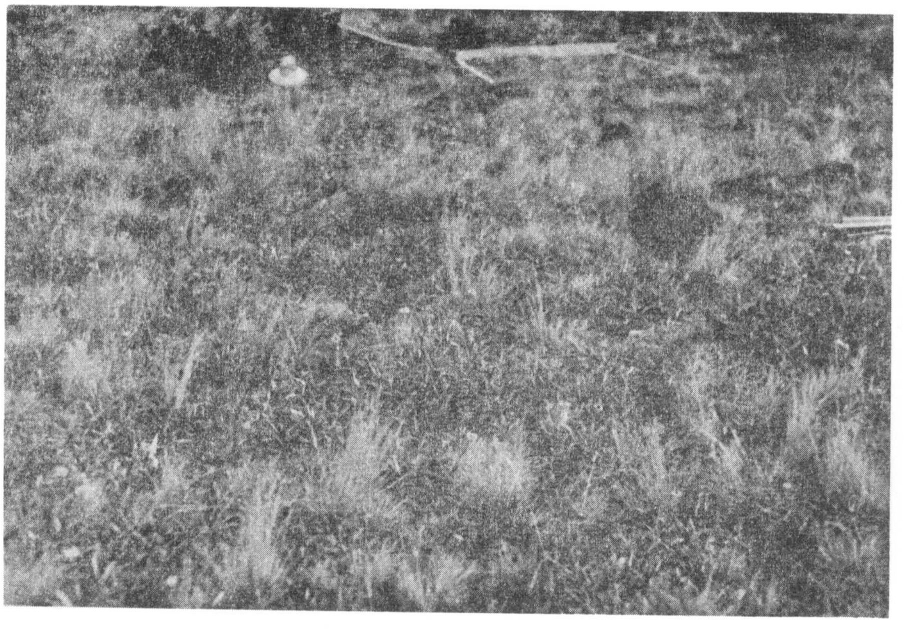
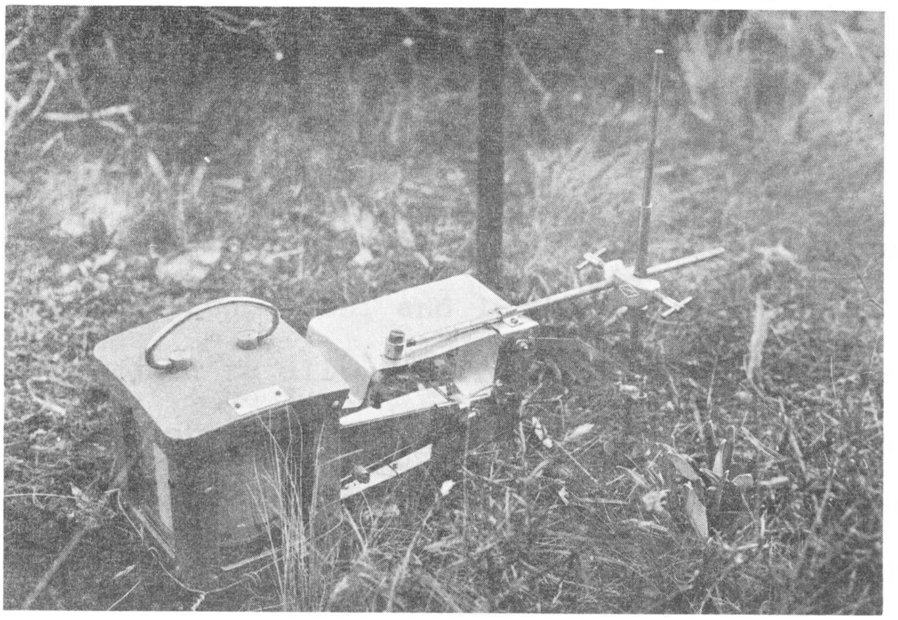


Plate 4. Site 3. Instrumentation and surface character of part of the site.

Plate 5. Site 3. The remainder of the site.

Plate 6. Site 4. The photograph shows the almost complete cover of tussock, low scrub with some celmisia.

Plate 7. Frost heave recorder.



All of these sites had ten T-bars (two of each length), eleven ¾ inch PVC tubes, and two (Site 4) or three (Sites 1, 2 and 3) columns of stones. Marked stones on the surface were used at Sites 1 and 3 only since Sites 2 and 4 had few stones at the surface. Young Pits were dug at Sites 2 and 4 only, because of the time taken to install them and because of the difficult nature of the regolith at the other sites.

To supplement the data from the four experimental sites and in order to obtain more complete coverage, ¼ inch PVC tubes were inserted at 30 randomly chosen points throughout the valley. These points were chosen by a method outlined Strahler (1956, p.589). The borders of a map of part of the valley were divided into 100 equal parts and 30 four-figure numbers taken from a table of random numbers. The first two digits gave the "Y" co-ordinates and the second two the "X" co-ordinates. The location of these points is shown in Figure 7.

Data Collection Programme

The field experiments began with the installation of the equipment on the 16th, 17th, and 18th of August, 1966. After a period of a month to allow instruments and markers to settle, routine measurements were made at fortnightly intervals until June 28th, 1967. During January and May more frequent measurements were made. On June 28th and 29th, when routine measurements ceased, the position of markers below the ground was traced and related to reference points.

Climate Records

Most of the climate records were obtained from the micro-climate station established by J.N. Rayner (Soons & Rayner, In Press). The situation of the instrument hut, the central plot and the two secondary plots is shown in Figure 7. The hut contains a Honeywell Brown 24pt. 2mv 2½ second full scan potentiometric recorder which prints one cycle of readings every 7½ minutes. Soil thermistors at the three plots are at 0.5, 2.0 and 15 cm below the surface with one at 40 cm below at the central plot. Also at the central plot are thermistors at 3 m and 12 m above the ground, an Eppley 16 junction pyranometer (recording solar radiation), a CSIRO radiometer (measuring net radiation) and three CSIRO flux plates measuring heat flow in the soil. A Lambrecht rainfall gauge provides a continuous record of rainfall at the central site while there are also rain gauges at the seven run-off plots (Figure 7), four of which are near the four main mass movement sites. Irregular records of wind run are kept at the Biological Field Station about a mile from the central plot.

Other Measurements

Short Period Measurements. As well as the routine measurement of T-bars, marked stones, and PVC tubes, a number of other variables were measured at the same time. The moisture content of soil samples taken from depths of 0-3 cm, 7.5-10 cm and 15-18 cm, below the surface at each site, was derived. These samples were brought to Christchurch in air-tight tins, weighed (in field condition), oven-dried for 24 hours at 105°C, left for 2 hours to come to equilibrium with atmospheric moisture, and weighed again. Moisture content was then expressed as a percentage of the dry weight of the soil. Although this method was not accurate as a measure of absolute moisture content, it was considered most satisfactory for comparative purposes.

From February 3rd, 1967, an indication of changes in soil strength, at the surface, was gained from a "SOILTEST" pocket penetrometer. The unconfined shear strength (in kg/cm^2) of the surface at each site was measured ten times and the mean of these readings used in analysis.

From April 14th, 1967, records of frost heave at the central climate plot were kept. The instrument used to measure heave consisted of a thermograph with the coil replaced by linkage connecting the pen-arm to a 3 cm disc resting on the ground surface (Plate 7). Since the depth of ground freezing has not been observed to extend more than 10 cm below the surface, and since the instrument was secured to a concrete block which was buried to a depth of 25 cm into the ground, it was thought to be free from the effects of frost heave. A wooden cover was placed over the recording unit to protect it from rain.

Site Characteristics. For the points where the ¼ inch PVC tubes were located, the angle of slope over a fifty foot segment of slope was measured with an Abney Level, and an estimate of the percentage vegetation cover made.

More detailed analysis of site characteristics was made for the four main sites. The angle of slope was measured by the same method as above, and the orientation of the slope measured with a prismatic compass.

Vegetation analysis was carried out using a line transect across each site. Analysis of vegetation cover within a one square foot quadrat was made at ten evenly spaced points along the line. The percentage cover for each species and the percentage bare area was estimated at each point and the average of these taken to represent the whole site.

Soil samples of two to three kilograms were taken from three points at each site and from three depths (0-10, 10-20 and 20-30 cm) at each of these points. At the same time the depth of the bedrock was recorded where possible. To estimate bulk density and organic matter content, an undisturbed sample was taken by driving a 500 cm^3 aluminium cylinder into the ground and then removing it with the sample.

On a scree slope above Site 3 (and closely resembling Site 3 in aspect, slope, and regolith characteristics), the orientation and inclination of the long axes of fifty stones greater than 4 cm in length was recorded at two points. This scree was chosen since it was thought that stones at Site 3 may have been disturbed during earlier work there.

LABORATORY ANALYSIS

Particle Size Analysis

All samples were air-dried and spread and quartered on a plastic sheet. One kilogram was chosen and oven-dried for dry sieve analysis, and for the twelve samples from 0-10 cm, 50-80 gm was taken for hydrometer analysis, and a further 50-80 gm used to determine the moisture content of the soil used in the hydrometer analysis since this could not be oven-dried. After drying and before dry sieving large stones were brushed to remove fines.

Hydrometer analysis consisted of soaking the sample for two hours, washing and removing large stones and dispersing the remainder in Sodium Oxalate solution. After the sample was dispersed it was agitated using a plunger in the settling jar, and hydrometer readings were taken at 3 minutes, 6 minutes 22 seconds, 25½ minutes, 1 hour 42 minutes, and 10 hours 30 minutes, and corrections were made for variations in temperature. These readings enabled the percentage of material smaller than 0.03, 0.02, 0.01, 0.005 and 0.002 mm to be computed.

The results of dry sieving and hydrometer analysis were plotted cumulatively. Where hydrometer analysis was carried out the cumulative curves from this and dry sieving could be fitted together. In most cases these fitted well though sometimes the amount of material smaller than 0.075 mm (the smallest sieve size) was less than the amount smaller than 0.03 mm (given by hydrometer analysis). The discrepancy was probably caused by either the aggregation of clay particles in dry sieving, or the differences in the samples used for dry sieving and hydrometer analysis.

The percentiles required for Folk Parameters (Folk, 1965) were read off the cumulative curves and the Graphic Mean(M_z), Inclusive Graphic Standard Deviation (σ_I), Inclusive Graphic Skewness (Sk_I) and Graphic Kurtosis (K_G) derived (Appendix I). The percentage clay ($<$ 0.002 mm) and Hazen's effective size (D_{10})

(Means & Parcher, 1963, p.61) were derived from the hydrometer analysis.

Atterberg Limits and Volume Change

The liquid, plastic and shrinkage limits were obtained for one sample from each site (Appendix I). The volume change of soil with moisture content change and over a freeze-thaw cycle, was obtained by measuring (with vernier calipers) the dimensions of a pat of soil in a small beaker. For volume change with soil moisture changes measurements of dimensions and weight were made at frequent intervals during oven-drying, and freezing and thawing dimensions were measured before and after freezing in a refrigerator.

Bulk Density

The bulk density of the undisturbed samples was given by the weight of the dry soil (in grammes) divided by the volume of the sample (in cm^3).

Organic Content

This was also obtained from the undisturbed samples. The weight of mineral soil (after removal of roots and treatment with Hydrogen Peroxide) was subtracted from the weight of dry soil to give a measure of organic content. While this was not very accurate it was thought to be a reasonable comparative measure.

METHODS OF DATA ANALYSIS

Statistical Analysis

The most used methods of statistical analysis were correlation and regression analysis and analysis of variance.

Correlation and regression analysis was used to establish a continuous record of soil moisture and to investigate the causes of slow mass movements. Most of this analysis was done on the University of Canterbury's IBM 1620. Analysis of variance was the main method used to investigate the variations between the main sites. These methods are considered in more detail in Appendix II.

Some of the basic assumptions of this type of analysis were at best only partially fulfilled in this study. Of fundamental importance to these methods is normality of parent populations, but usually the sample size was too small to detect any departures from normality. In some cases it was found that logarithmic transformation gave closer approximation to the normal distribution. Analysis of variance is considered by Box (1953, p.318) to be able to withstand moderate departures from normality.

Another prerequisite for statistical analysis is objective sampling. The four main sites were not chosen with this in mind, but the siting of the ¼ inch PVC tubing was considered to be free of bias. Since data collection was made at regular intervals it is unlikely that there was any bias in sampling over time. Most of the limitations in the application of statistical analysis to this study stemmed from problems of sample size.

Fabric Analysis

The orientation and inclination measurements were plotted as points on Schmidt nets and contoured. Both two- and three-dimensional vector analysis were applied (Appendix III). Cailleux's parallel index (the percentage of particles within 45° of the slope direction) and "strict" parallel index (within 30° of the slope direction) were also derived for comparison with other work.

CHAPTER 3 THEORY OF SOIL CREEP

TYPES OF SOIL CREEP

Soil creep is one of a wide range of mass movement processes that can be distinguished according to the nature of shear, the characteristics of the material involved, and the speed of movement. Sharpe has defined the general term "creep" as the "slow downslope movement of superficial soil or rock debris, usually imperceptible except to observations of long duration." (Sharpe, 1960, p.21). Parizek & Woodruff (1957) note that the term "creep" has suffered from over-use. They suggest that, because the mechanics involved in other mass movement processes are the same, soil creep should be distinguished by its imperceptibility. While this is important for a definition of soil creep, Terzaghi (1950) has shown that it is possible to distinguish different types of creep on the basis of the mechanisms involved. He suggested two types of soil creep;

(1) Continuous creep

(2) Seasonal creep.

Continuous Creep

This movement occurs as the result of forces which operate in the same direction all the time. Flow occurs only on unstable slopes, and takes place by sliding of particles over one another. The theory of this type of movement is fairly well known. Kirkby (1965) has shown that on a long straight slope at angle θ, made up of a cohesive clay (cohesion c) and with vertical thickness z, the following rates of movement occur at the surface:

$$0 \qquad \text{if } z \leqslant c/\ g$$

$$\text{and} \quad \frac{\rho^2 g_2{}^2 z^2 - c^2}{2\eta\rho g} \sin\theta \qquad \text{if } z > c/\ g$$

where ρ = density

η = viscosity in the equation for a Bingham plastic

g = acceleration due to gravity.

That is, this type of movement occurs only when the stresses exceed a certain value which is determined by the properties of the material.

Seasonal Creep

This type of movement occurs as a combination of the action of either cyclic or random forces, and gravity. While continuous processes cause movement only where slopes are unstable, seasonal processes, such as the expansion of soil with moisture changes, freezing and thawing of the soil moisture, and temperature changes, occur on all slopes. These forces, in combination with gravity, typically produce very small changes, and the associated rates of movement are so small as to be imperceptible.

Discussion

It is considered likely that where there is no evidence of slope failure caused by continuous processes, any creep measured will be seasonal. As there is no evidence of continuous creep in the Chilton Valley, the soil creep here is probably seasonal and is defined as the slow downslope movement of superficial soil resulting from a combination of seasonal forces and the action of gravity. All mention of soil creep which follows refers to this type of movement unless otherwise stated.

THEORIES OF SOIL CREEP

Two different approaches to the development of the theory of soil creep have been made:

(1) The first attempts to describe the processes operating (the causes of movement) and to suggest general laws of soil creep.

(2) The second attempts to formulate mathematically a theory of creep, either deductively (where assumptions are made about the processes operating), or inductively (where reasoning from basic physics is applied).

General Approaches

Most of the approaches of this type are discussed by Blong (1966). The most significant contribution was made by Gilbert (1909). He stated that any force which disturbed the arrangement of particles and thus permitted motion among them, promoted flow or creep. As possible causes he suggested expansion and contraction of the soil due to freezing and thawing, heating and cooling, and wetting and drying of the soil, while he also recognised the importance of other influences such as livestock, rainbeat, and the growth and decay of plant matter. Sharpe (1938) also considered the causes of soil creep but his main contribution was a collation of previous work. Other workers such as Schumm (1956b) and Young (1958) have attempted to explain the action of processes causing soil creep in particular areas but have added little to Gilbert's original statement.

Mathematical Approaches

The only published works on the mathematical formulation of a theory of soil creep are by Davison (1889), Culling (1963) and Kirkby (1965). The most important development in this field has come since the introduction of the dynamic approach as a basis for geomorphology (Strahler, 1952).

Davison. By considering the movement of a line of particles normal to the slope surface, Davison deduced the profile of soil movements caused by freezing and thawing of the soil moisture. He showed that expansion during freezing occurred normal to the surface, while contraction, affected by the cohesion of soil particles and by gravity, occurred in a line between the vertical and normal to the surface. With the assumptions that the displacement of a particle was proportional to its distance from the surface, and that particles descended vertically during the thaw (thereby ignoring the cohesion factor), Davison demonstrated that for a single freeze-thaw cycle, a line of particles would remain in a straight line but tilted downslope (Figure 8). Since over a period of time, there would be numerous frosts of differing intensities, the resulting magnitudes of cumulative expansion and contraction would decrease logarithmically with depth. Integrating the resulting profile

Figure 8. The effect of soil freezing according to Davison (1888)

AB - ground surface

CD - depth of freezing

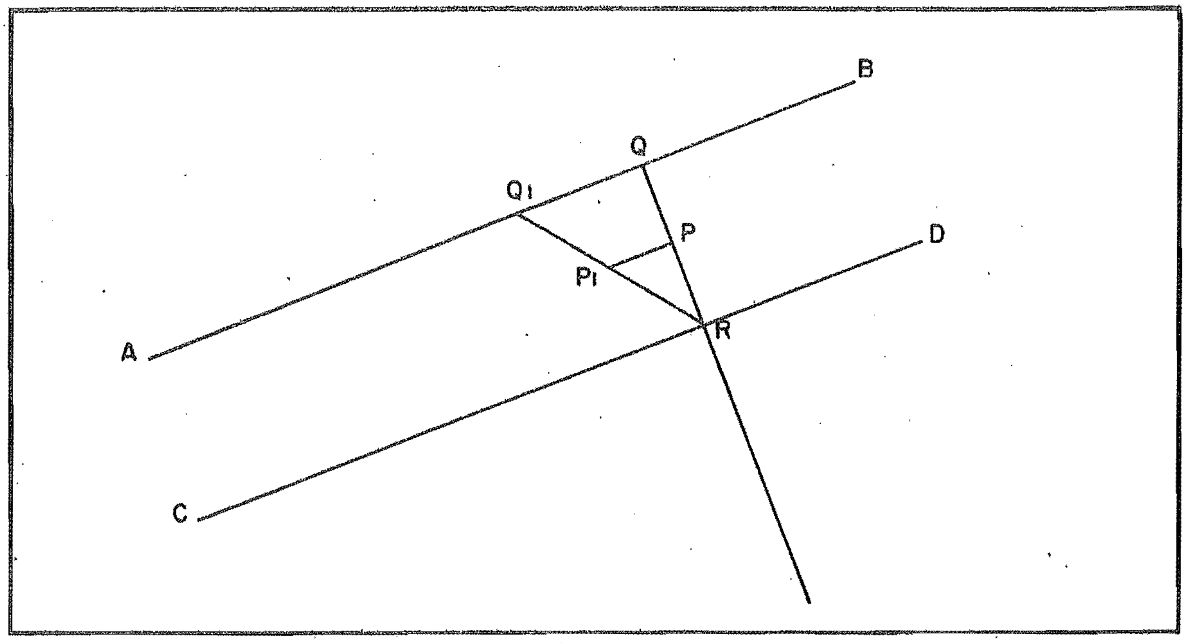
QPR - line or particles before freezing

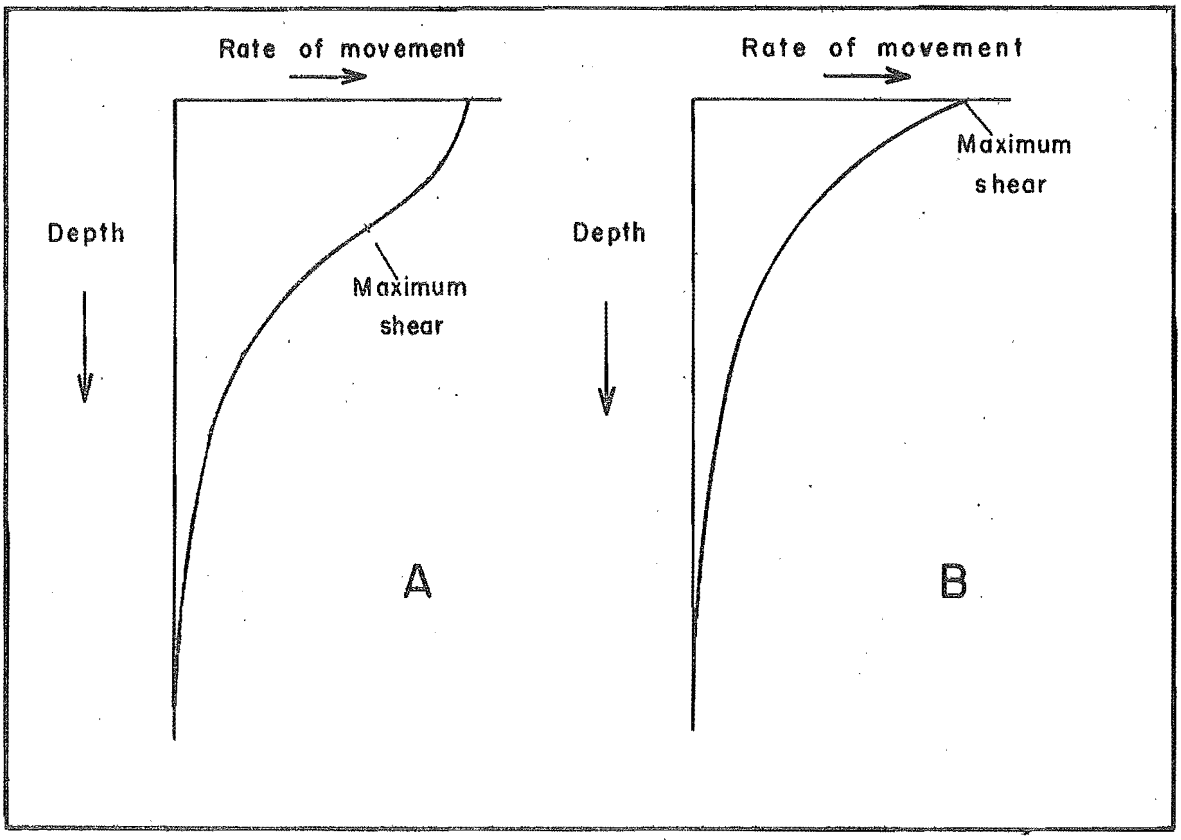
Q_1P_1R - line of particles after thaw.

Figure 9. Velocity profiles of soil movement according to different theories of soil creep

A. Kirkby (1965)

B. Davison (1888) and Culling (1963).


B
Q
Q1
P
D
P1
R
A
C


Rate of movement
Depth
Maximum shear
A
Rate of movement
Depth
Maximum shear
B

normal to the slope gives a curve with its concavity down-slope (Figure 9).

Culling. The dynamic approach mentioned above has introduced the possibility of developing a theory of soil creep on a rational basis, involving a description of processes in Newtonian terms followed by reasoning based relations among forces, motions and states. However, a completely inductive approach is still not possible because of the lack of knowledge of the processes involved. Culling, therefore, assumed an ideal soil cover of similar sized, regularly shaped particles in which boundary effects could be neglected. The random movements of individual particles caused by molecular and gravitational stresses were then considered in terms of frequency functions, and the resultant development of the model defined on a probability basis. He showed that two factors influence the probability of movement in response to stress; on the one hand, gravity exerts a downward influence tending to cause compaction of the soil, while on the other hand, the variation in packing density which results from this should lead to a slow upward diffusion of particles from high density areas to low density ones. These two influences will reach a steady state in which the volume of pore space decreases exponentially with depth. Since the movement of particles in response to molecular stresses can only occur where sufficient pore space exists to allow it, movement also decreases exponentially with depth. The tangential component of gravity introduces bias so that the most likely movement (where it can occur) is downslope, giving a velocity profile which is concave downslope (Figure 9).

As molecular forces imparting random motion, Culling invoked thermal expansion and potential effects, surface tension and capillary forces, cohesive and absorptive tendencies, chemical, electrical, and magnetic phenomena and the expansion of freezing water in the interstices of the soil. Because of the restraint of the available pore space, the number of displacements was considered to be small in relation to the number of times the forces operated.

Kirkby. While Culling dealt with a complete range of mechanisms and made assumptions regarding the nature of the soil cover, Kirkby considered the movement of a single particle over a cycle of expansion and contraction. By investigating the forces acting he derived a rate of shear and by integration the total horizontal movement. This analysis showed that:

(1) creep rate was roughly proportional to the sine of the slope angle,

(2) depth below the surface was an important factor in amounts of creep at small depths,

(3) the form of the velocity profile was different from that derived by Davison and Culling since the maximum rate of shear occurred at a point below the surface and decreased to zero at the surface and also with greater depth (Figure 9). Kirkby also extended this general theory of soil creep to a theory of soil creep caused by soil moisture changes. The theory is well suited to this adaption since moisture changes

are effective to greater depths than are other changes such as heating and cooling and freezing and thawing.

Discussion. It is apparent that Davison's theory deals with a single process having special effects (noted by both Culling and Kirkby), and therefore cannot be considered a general model.

Culling and Kirkby, however, seek to explain more complex processes and their success depends mainly on their initial assumptions. Culling's theory is particularly handicapped by the failure to take boundary conditions into consideration. The main weakness in Kirkby's argument is the implicit assumption that all stresses cause movement. These basic assumptions are also partly revealed in the differing velocity profiles (Figure 9). In Culling's theory the overruling feature is the need for available pore space before movement can occur and the maximum shear therefore occurs where the pore space is greatest, at the surface. In Kirkby's theory the weight of soil above a certain point is a more important consideration in the rates of shear, and since all stresses are capable of causing movement, the rate of shear decreases to zero at the surface (because of the decreasing weight of soil above) and also with depth (because of the decreasing magnitude of cyclic forces).

Further comparison of the velocity profiles given by these two theories is unwise since no indication of the vertical scale is given by either Culling or Kirkby. It is possible that the inflexion in Kirkby's velocity profile occurs very near the surface and the difference between the two profiles is much less than that indicated by Figure 9. Although Culling's profile seems more akin to what has been found, this may only reflect that most observations of soil creep refer to that caused by freezing and thawing of the soil moisture.

Culling's theory seems to hold more promise for further development providing the assumptions regarding soil characteristics and boundary effects can be relaxed. To develop a more complete theory from consideration of the movement of one particle over one cycle would be much more difficult.

CAUSES OF SOIL CREEP

Many different causes of soil creep have been suggested, and most of these have been listed by Sharpe (1938) (Table 3). In the Chilton Valley many of these causes probably have some effect, and evidence for some of these, for example ice needles (Plate 8), and animal scratchings (Plate 9), was observed. On both theoretical and empirical grounds it seems that "seasonal" forces associated with climatic variations are most important in causing soil creep. The main forces are thought to be heating and cooling, freezing and thawing, and wetting and drying of the soil. The relative importance of these forces can be estimated by calculating the gross annual expansion, and this provides a working hypothesis for further work. Kirkby (1965) showed that gross annual expansion, l, could be derived from the formula;

Table 3

Causes of Soil Creep (after Sharpe)

A. Direct downslope movement due to:
   1. Wedging and prying by:
      a. Growth of plants
      b. Expansion of mantling vegetable matter owing largely to wetting
      c. Swaying of trees and bushes in wind
      d. Expansion of water freezing in joints or cracks
      e. Hydrostatic pressure of water in joints or cracks
      f. Expansion of soil due to heating: diurnal, annual, irregular
      g. Expansion of soil due to wetting, including swelling of colloidal matter
      h. Animals, including man

   2. Filling and close, largely from the uphill side, of cavities, cracks, or depressions caused by:
      a. Burrowing or excavating animals including man
      b. Decay of plant roots and other organic matter
      c. Gullying or undercutting by streams and rainwash
      d. Removal of soluble fractions of rocks or minerals
      e. Removal of fine grades of material by slope wash and rills
      f. Slipping away of portion of slope
      g. Shrinkage of soil due to:
         (1) Dessication
         (2) Cooling

   3. Removal of products of weathering

   4. Increase of load
      a. Permanent, caused by addition of material up slope by landslide, mudflow, building of alluvial fans etc.
      b. Temporary, caused by:
         (1) Rainfall, snowfall, snow or ice avalanche
         (2) Walking or animals, including man

   5. Disturbance of equilibrium by earthquakes, winds or animals, including man

B. Indirect downslope movement caused by:
   1. Frost heaving
   2. Expansion due to heating.

Plate 8. Ice needles. Note the soil on top of the ice needles.

Plate 9. Hare scratchings. The lens cap is 5 cm in diameter.

$$1 = n.u.v.$$ where n = number of cycles per year

u = coefficient of expansion

v = range of the variable in an average cycle.

The gross annual expansion caused by freezing and thawing, heating and cooling, and wetting and drying of the soil is shown in Table 4.

The gross annual expansion caused by temperature changes and by freezing and thawing ~~are~~ similar to those derived by Kirkby (1965) but he calculated a value of 32% for moisture changes. Despite this Kirkby decided that soil moisture changes were of much greater importance than freezing and thawing of the soil. However he also showed that the maximum depth of freezing was only 2.5 cm and the mean depth probably half of this. In the Chilton Valley a depth of freezing of 10 cm has been observed. If the average depth to which moisture changes and freezing and thawing are incorporated in the calculations, a value of 20 cm taken for moisture changes and 1 cm and 4 cm for freezing and thawing in the Deugh Basin and the Chilton Valley respectively, the gross expansion of the top 20 cm of soil in the Chilton Valley is 9.5% due to moisture changes and 20.4% due to freezing and thawing. For the Deugh Basin the values are 5.1% caused by freezing and thawing and 32% caused by moisture changes.

This anlaysis provides the hypothesis that the most important cause of soil creep in the Chilton Valley is the freezing and thawing of soil moisture. This hypothesis is

Table 4

Amounts of Gross Annual Expansion

Cause	Coefficient of expansion	Number of cycles/year	Change over an average cycle	Gross annual expansion
moisture changes	.02%/1%	28	17%	9.5%
temperature changes	.001%/°C	365	12°C	4.3%
freezing and thawing	2%/freeze	50[1]	1 freeze	102.0%

[1] recorded at 0.5 cm below the surface.

examined in the following chapter.

CHAPTER 4 FIELD MEASUREMENTS OF SOIL CREEP

In this chapter the two primary concerns are to discuss the rates of soil creep and the causes of creep in the Chilton Valley. The analysis of creep rates includes an attempt to demonstrate some controls of creep and to calculate an average rate of creep for the valley. The investigation of causes consists of an examination of the effects of freezing and thawing of soil moisture and changes of soil moisture content, on soil movement. Before considering the results of the soil measurements, however, the nature of the sites at which the experiments were conducted will be examined in detail.[1]

SITE CHARACTERISTICS

Most of the results of the investigation of site characteristics are presented in tabular form. The aspect and slope of the four sites are shown in Table 5, while the result of the vegetation surveys are shown in Table 6. Regolith characteristics are summarized in Tables 7, 8 and 9, and presented in more detail in Appendix IV. The slope angle and percentage vegetation cover for the points where ¼ inch

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1 - Most of the data presented in this thesis has been subjected to some analysis. The raw data on which this was based is contained in a separate volume, "Basic data from a study of mass movements in the Chilton Valley", lodged in the University of Canterbury Library. This includes measurements of T-bar movement, scree particle movement, fabric measurements, soil moisture and penetrometer records, daily rainfall and radiation data, and freeze-thaw cycles recorded.

Table 5

Aspect and Slope of the Main Sites

Site	Aspect (degrees)	Slope (degrees)
1	121	27
2	143	34
3	300	27
4	205	16

Table 6

Vegetation Characteristics of the Main Site

	% of Total Area						
Site	Celmisia	Cassinia	Tussock	Cyath-odes	Moss Sp.	Manuka	Bare
1	13.5		9.0		23.5		54.0
2	43.8		21.7	7.5	25.5	1.0	0.5
3							100.0
4	4.0	6.5	34.0	4.0	28.5		19.0

Table 7

Summary of Particle Size Parameters

Site	$M_Z(\phi)$	$_I(\phi)$	Sk_I	K_G
1	0.40 to -4.4	1.5 to 3.2	-.07 to -.55	0.74 to 3.43
2	1.3 to -1.7	2.5 to 3.4	-.05 to 0.21	0.69 to 0.87
3	2.6 to -4.2	1.5 to 4.0	-.01 to -.78	0.67 to 2.28
4	1.1 to 0.2	2.6 to 3.4	-.04 to -.42	1.03 to 1.38

Table 8

Other Particle Size Parameters

Site	D_{10}(mm)	Clay content % sample	 % 2 mm
1	0.95	1.0	4.5
2	0.3	0.8	1.6
3	0.03	3.8	9.4
4	0.03	4.1	5.6

Table 9

Other Regolith Characteristics

Site	Depth to bedrock (cm)	Atterberg Limits (%) Liquid	Plastic	Shrinkage	Plasticity Index	Bulk Density gm/cm^3
1	40	52	47.3	18	4.7	.72
2	90	86	77.3	24	8.7	.67
3	?	33	21.8	16	11.2	.68
4	150	64	46.5	18	17.0	.6

PVC tubes were measured are shown in Table 10.

RATES OF SOIL CREEP

The long period measurements of soil creep were somewhat confusing since different methods gave contradictory results.

Young Pits

For both Young Pits the change in position of the markers was too small to be measured.

¾ inch PVC Tubing

In almost all cases no downhill movement of the tubing could be detected and in many cases it retained its original curvature. Several of the tubes had a slight accumulation of material behind them as shown in Plate 10.

T-Bars

Table 11 shows the tilts that occurred over the whole period. The expected relation between the amount of movement measured and the length of T-bar was not borne out by the results, though there seemed to be a greater variation of total movements recorded by the shorter T-bars. This variability was, however, characteristic of all the T-bar results. At Sites 1 and 3 there was a definite downslope component measured but Sites 2 and 4 had smaller movements, both uphill and downhill.

Columns of Stones

The results of the tracings of the columns of stones are shown in Figure 10. Only one column was traced at Site

Table 10

Vegetation Cover and Slope of Secondary Sites

Tube Number	Vegetation (%)	Angle of Slope (degrees)
1	20	29
5	0	20
6	90	35
9	90	12
11	100	29
13	100	14
14	30	30
16	60	18
18	100	30
22	100	25
25	0	29
26	0	28
28	40	34
30	80	30

Table 11

Total T-bar Tilts

Site	1	2	3	4
T-bar lengths (cm)				
65	+54	+27	+83	+23
65	+1	+1	+101	-3
50	+54	-33	+142	-54
50	-36	-220	-15	-15
35	+187	-25	+544	+10
35	+12	0	+465	-29
25	+30	-23	+73	+34
25	+101	+61	+28	-1
20	+977	+48	+484	+53
20	+32	-5	+271	+26

T-bar tilt measured in minutes: +ve - downslope

-ve - upslope

Plate 10. $\frac{3}{4}$ inch PVC tube. Note the slight accumulation of material behind the tube.

Plate 11. $\frac{1}{4}$ inch PVC tube. Photograph taken just before tracing at the end of the period,

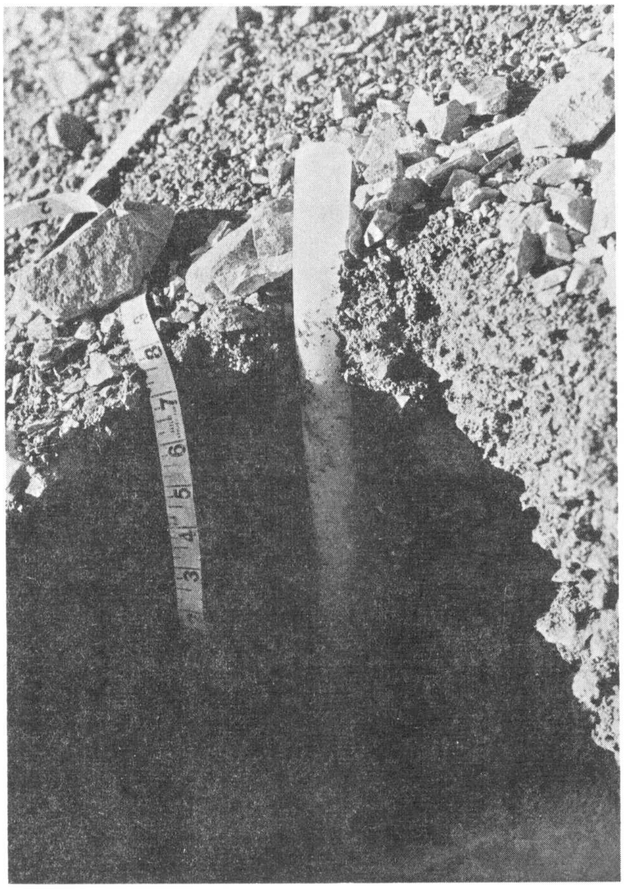
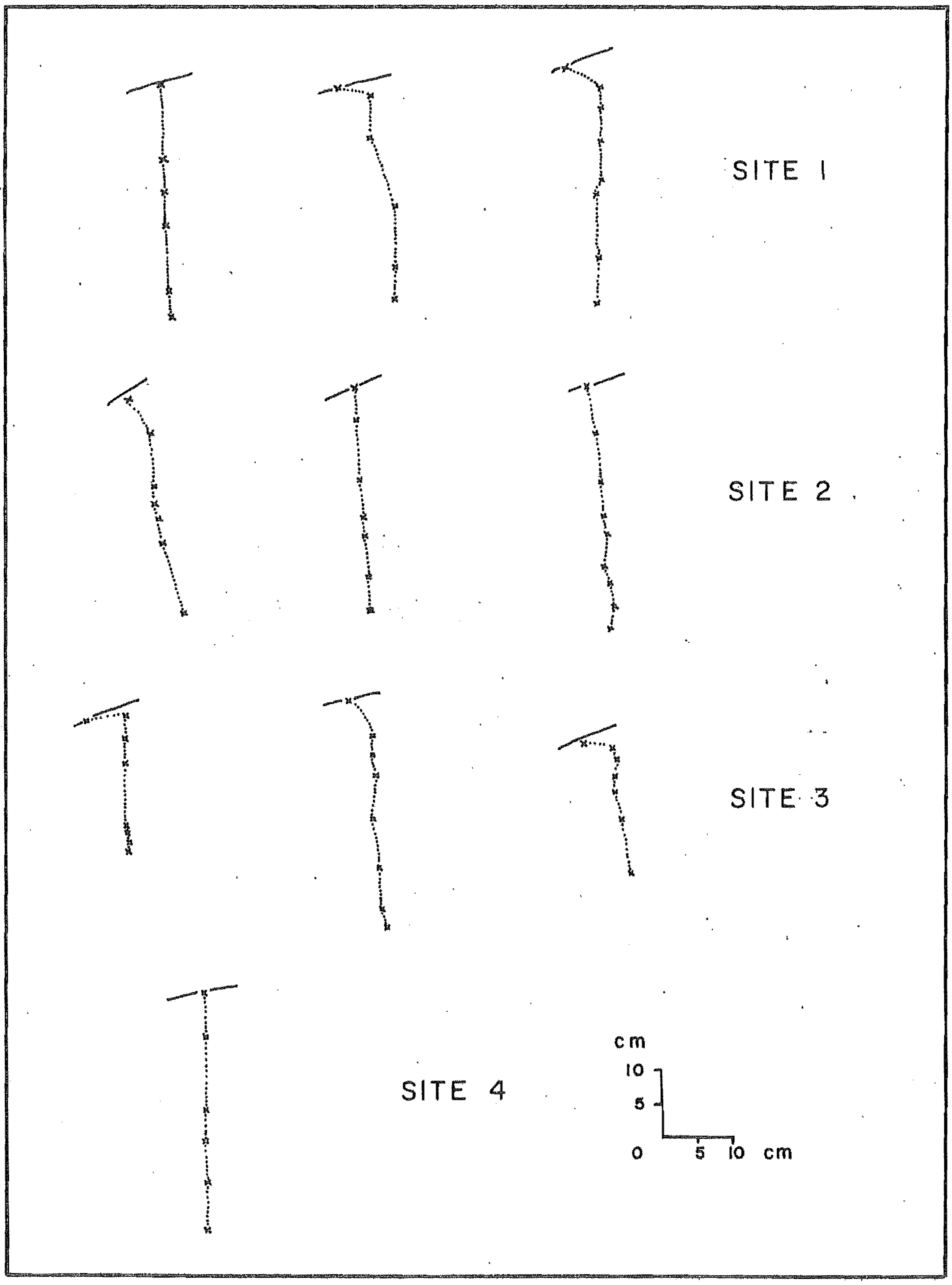

8
7
6
5
4
3

Figure 10. Movement of columns of stones. Crosses mark the final position of the marked stones.


SITE 1
SITE 2
SITE 3
SITE 4
cm
10
5
0
5
10
cm

4 since the other one was accidently disturbed before it was located.

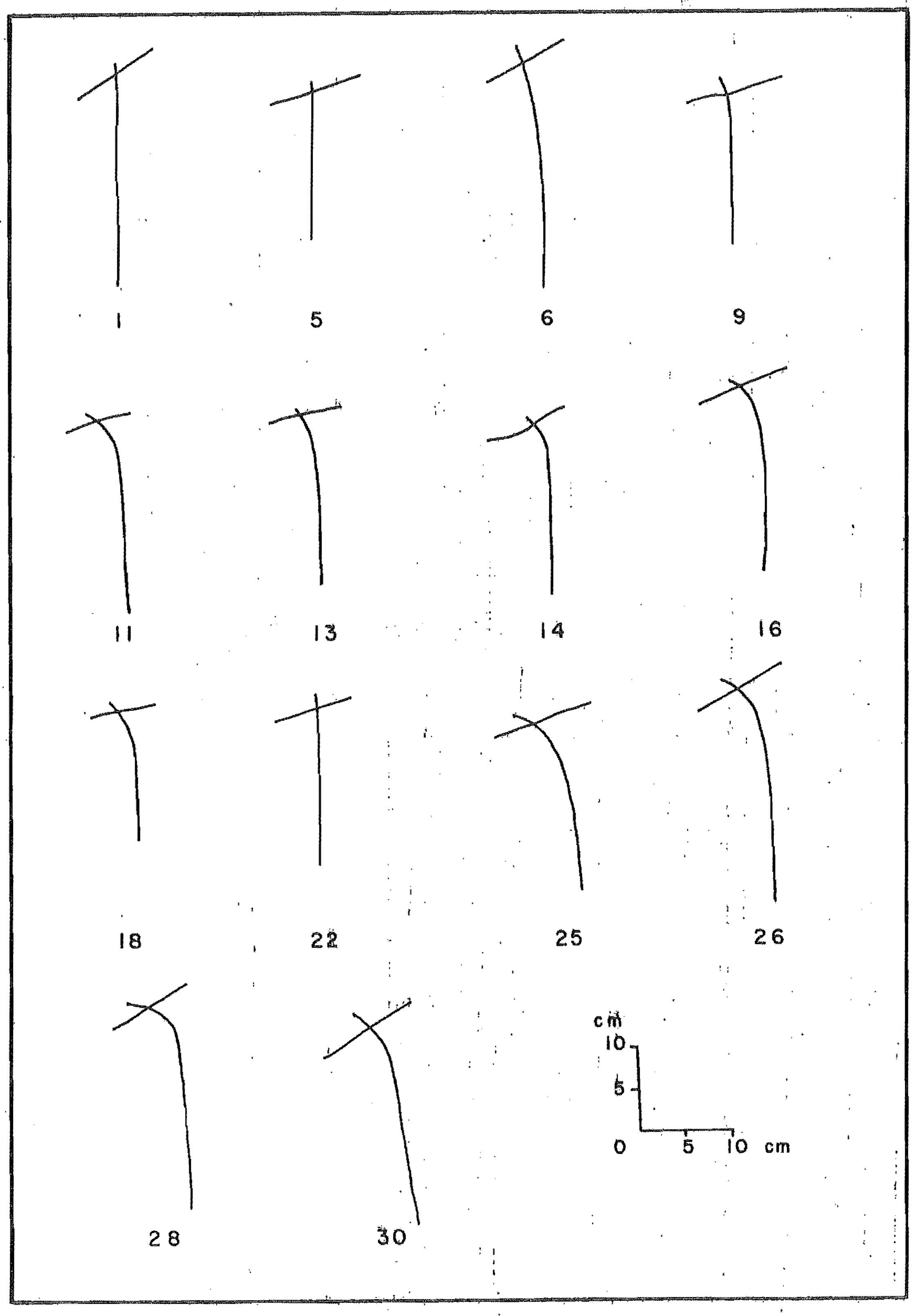
¼ inch PVC Tubing

The final traces of the PVC tubes are shown in Figure 11. Plate 1l shows one of these tubes. Of the 30 tubes originally inserted only 14 were traced. This high rate of loss (53%) was due to removal of the tubes (probably by birds) and to the fact that a small percentage (7%) could not be relocated.

Discussion

The results of different attempts to measure soil creep warrants discussion, which may suggest reasons for the variations between the results. It is reasonable to assume that the ¾ inch PVC tubing had a much greater "anchoring" effect on the soil around it than the ¼ inch tubing. This problem was increased by the fact that movement occurred mainly in a shallow surface layer, as shown by the columns of stones. The reason for the lack of movement recorded by the Young Pits is not so clear. Emmett (1965) has demonstrated that the type of markers used by Young, Kirkby and in this study, probably do not reflect the actual movement taking place. Also the two Young Pits were located at sites where comparatively small amounts of movement were indicated by T-bars; that is, the bias introduced in choosing sites for location of the Young Pits probably affected the results. In contrast to this the ¼ inch PVC tubes were much more likely to move with the soil, and were located randomly.

Figure 11. Movement of $\frac{1}{4}$ inch PVC tubes. The diagram shows the final position of the fourteen tubes traced.


1
5
6
9
11
13
14
16
18
22
25
26
28
30
cm
10
5
0
5
10 cm

ANALYSIS OF CREEP RATES

Variation Between Sites

Analysis. The causes of variations between sites can only be tentatively suggested because of the great variability in site characteristics and amounts of movement recorded within sites. Since an extremely small sample of only four sites has been used, statistical analysis of between sample variation has only limited use. Such analysis is made even more difficult by the great variation experienced at each site.

An analysis of variance on the T-bar results from all sites showed that Site 3 was significantly different from Sites 2 and 4, but that all other sites were not significantly different (Table 12). Columns of stones were not used very much in this analysis because of the doubtful accuracy and small number at each site.

The variation in the slopes of the four sites was not sufficient to bring out any trend although theoretically there should have been a relation between movement and the sine of the angle of slope. Aspect also appeared to be of little importance.

The amount of vegetation, however, seems to have a very important effect on the amount of soil movement. The average T-bar movement of the four sites was correlated with the percentage bare area and a correlation coefficient of 0.97 (significant at the 0.05 level) resulted. No significant relationships with any particular species could be discerned.

Table 12

Analysis of Variance - Total Tilts

Sites	d.f.	Between mean square	Within mean square	F	Signif-icance (%)
1-2	1/18	95766.5	45499.7	2.1047	NS
1-3	1/18	2915.6	68095.0	0.0428	NS
1-4	1/18	131847.3	45482.3	2.8989	NS
2-3	1/18	230614.7	22194.2	10.3908	99.99
2-4	1/18	12.8	1030.1	0.0124	NS
3-4	1/18	227258.4	22167.8	10.2517	99.99

Regolith characteristics were treated in some detail but it was often difficult to establish differences between sites. Tables 13, 14 and 15 show the results of analyses of variance on the mean size, skewness and kurtosis values for samples from all sites. (Sorting values were uniformly poor). Where differences (in the other Folk Parameters used) could be discerned, they could not be related to any variations in movement. Though it might be expected that smaller grain sizes and a greater percentage of fines would be more conducive to soil creep (as suggested by Young 1958), differences in mean size and skewness were too small to indicate such an effect. Although there were differences in kurtosis between samples at all depths from Sites 2 and 4, the differences were more due to the uniformity of values within sites than to large differences in the kurtosis values. Analysis showed that there was no significant difference in the silt-clay content of samples from all sites. Although there were differences in effective size between some sites (Table 16), these could not be directly linked with movement.

Other regolith features showed little or no relationships with the amounts of movement recorded at the four sites. While there was a considerable range of soil consistency as shown on the Casagrande chart (Figure 12), these variations were apparently not associated with differences in amounts of movement. The averages of penetrometer measurements were similar for all sites. These measurements were plotted

Table 13

Analysis of Variance - Mean Size

Site	d.f.	Between mean square	Within mean square	F	Significance (%)
0-10 cm					
1-2	1/4	0.7141	0.4407	1.6206	NS
1-3	1/4	6.027	4.035	1.7168	NS
1-4	1/4	11.0432	0.4963	6.434	93.0
2-3	1/4	3.193	3.7844	0.8437	NS
2-4	1/4	6.1468	0.2456	25.0012	99.3
3-4	1/4	0.4777	3.8310	0.1244	NS
10-20 cm					
1-2	1/4	17.9920	1.5233	11.8114	97.5
1-3	1/4	0.6208	3.2487	0.1911	NS
1-4	1/4	17.5104	1.5162	11.5488	97.5
2-3	1/4	11.9286	1.9488	6.1212	94.0
2-4	1/4	0.0033	0.2162	0.0151	NS
3-4	1/4	11.5371	1.9417	5.9419	NS
20-30 cm					
1-2	1/3	6.5333	4.2226	1.5472	NS
1-3	1/3	3.4544	4.596	0.7516	NS
1-4	1/3	9.2519	3.8478	2.4045	NS
2-3	1/4	24.3614	0.9496	25.6562	99.3
2-4	1/4	0.2948	0.3883	0.7592	NS
3-4	1/4	30.0161	0.6684	44.9053	99.5

Table 14

Analysis of Variance - Inclusive Graphic Skewness

Site	d.f.	Between mean square	Within mean square	F	Significance (%)
0-10 cm					
1-2	1/4	0.0468	0.0018	2.5537	NS
1-3	1/4	0.0001	0.0231	0.0026	NS
1-4	1/4	0.0794	0.0206	3.8463	NS
2-3	1/4	0.0433	0.0384	1.128	NS
2-4	1/4	0.0043	0.0359	0.1186	NS
3-4	1/4	0.0748	0.0407	1.8367	NS
10-20 cm					
1-2	1/4	0.3902	0.0212	18.4053	NS
1-3	1/4	0.04	0.0672	0.5958	NS
1-4	1/4	0.1176	0.0125	9.408	97.5
2-3	1/4	0.1803	0.0828	2.1778	NS
2-4	1/4	0.0794	0.0281	2.8233	NS
3-4	1/4	0.0204	0.0766	0.2667	NS
20-30 cm					
1-2	1/3	0.0464	0.039	1.1894	NS
1-3	1/3	0.1673	0.0444	3.7652	NS
1-4	1/3	0.0163	0.0422	0.3974	NS
2-3	1/4	0.4874	0.005	97.8614	99.9
2-4	1/4	0.0096	0.0545	0.1763	NS
3-4	1/4	0.3602	0.0073	40.1337	99.6

Table 15

Analysis of Variance - Graphic Kurtosis

Site	d.f.	Between mean square	Within mean square	F	Significance (%)
0-10 cm					
1-2	1/4	0.375	0.0908	4.1322	NS
1-3	1/4	0.0451	0.2226	0.2024	NS
1-4	1/4	0.0504	0.0943	0.5349	NS
2-3	1/4	0.1601	0.1403	1.1412	NS
2-4	1/4	0.1504	0.0119	12.6297	97.5
3-4	1/4	0.0002	0.1463	0.001	NS
10-20 cm					
1-2	1/4	1.0168	0.388	2.6204	NS
1-3	1/4	0.4538	0.861	0.527	NS
1-4	1/4	0.3553	0.395	0.8995	NS
2-3	1/4	0.1121	0.229	0.4893	NS
2-4	1/4	0.17	0.013	13.1188	97.5
3-4	1/4	0.006	0.449	0.0124	NS
20-30 cm					
1-2	1/3	1.9406	1.2104	1.6033	NS
1-3	1/3	0.6483	1.3053	0.4967	NS
1-4	1/3	0.8036	1.2205	0.6584	NS
2-3	1/4	0.432	0.0777	5.5594	90.0
2-4	1/4	0.3083	0.0141	21.816	99.0
3-4	1/4	0.0104	0.0853	0.1221	NS

Table 16

Analysis of Variance: Effective Size

Sites	d.f.	Between mean square	Within mean square	F	Significance (%)
1-2	1/4	0.0704	0.057	1.2414	NS
1-3	1/4	0.1412	0.0554	2.5477	NS
1-4	1/4	0.1405	0.0555	2.5329	NS
2-3	1/4	0.0122	0.0013	9.6825	96.0
2-4	1/4	0.012	0.0013	9.3515	96.0
3-4	1/4	0.0000	0.00004	0.000	NS

Figure 12. Consistency of soil from the four main sites.

a. Inorganic clays of low plasticity

b. Cohesionless soils

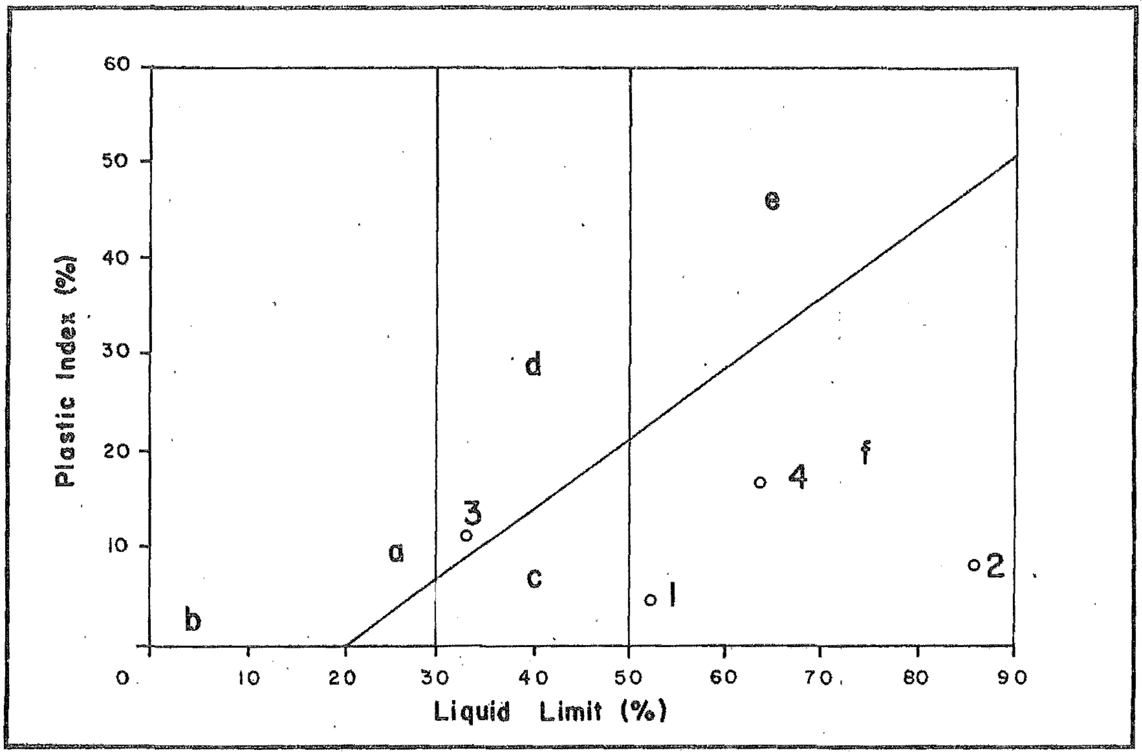
c. Inorganic silts of medium compressibility and organic clays.

d. Inorganic clays of medium plasticity

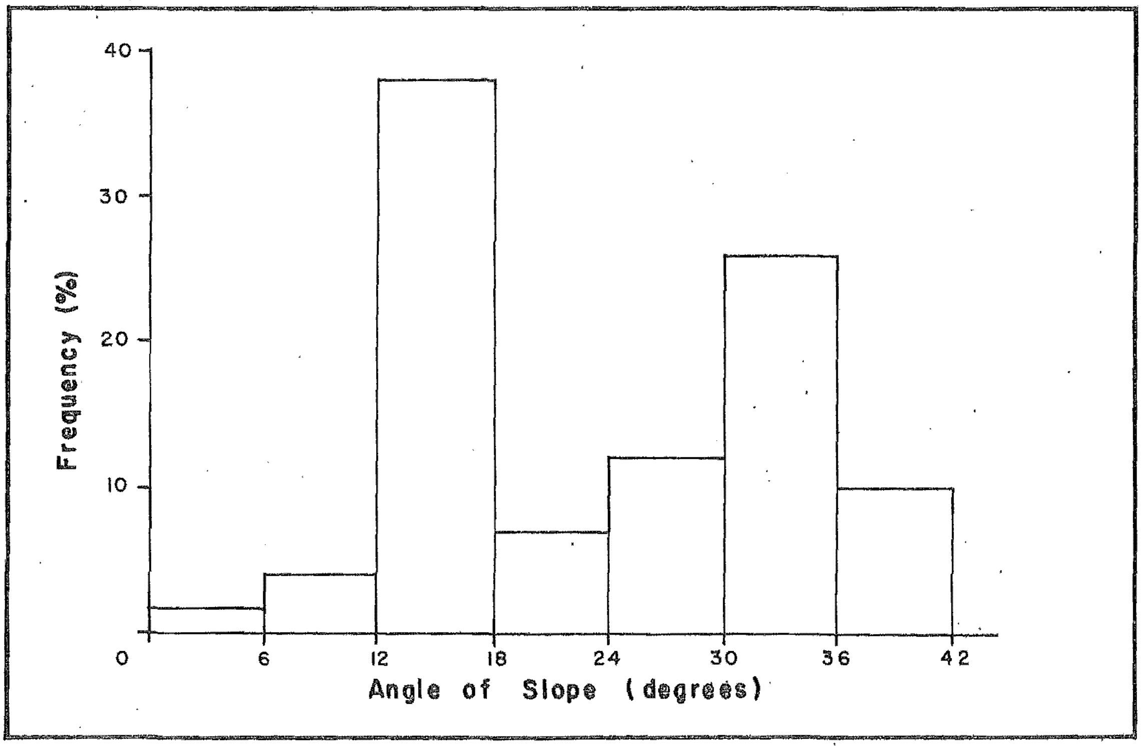
e. Inorganic clays of high plasticity

f. Inorganic silts of high compressibility and organic clays.

Figure 13. Frequency distribution of slopes. This refers to a portion of the valley sampled for ¼ inch PVC tube locations.



Plastic Index (%)
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
Liquid Limit (%)
a
b
c
d
e
f
1
2
3
4



Frequency (%)
40
30
20
10
0
6
12
18
24
30
36
42
Angle of Slope (degrees)

against the surface moisture contents measured at the same time and the correlation and regression coefficients obtained are shown in Table 17. The regression equations for Sites 1, 2 and 4 were similar but for Site 3 a greater range of shear strength was associated with changes in moisture content. This suggested a slight tendency for greater amounts of movement to occur where there were larger changes in soil strength associated with moisture changes.

Discussion. The results of this part of the anlaysis are at best tentative. The most significant influence on the amount of soil creep appears to be the amount of bare area. Apart from this no other single factor has an important, consistent effect on the data under consideration.

Creep Rates in the Chilton Valley

Because of the failure of the Young Pits and the ¾ inch PVC tubing to indicate any movement the attempts to establish an average rate of soil creep relied on the ¼ inch PVC tube results. This seriously limits the value of comparisons with the results obtained by Young (1960 and 1963) and Kirkby (1965), who used only Young Pits. However some comparisons are possible, especially with the results obtained by Caine (1963) who used similar methods to those of this study.

Analysis. The velocity profiles given by the PVC tubes were analysed in different ways. To compute volumetric creep, the area between the surface, the assumed initial position of the tube and the final position, was measured in square

Table 17

Relation Between Soil Strength and Moisture Content

Site	r	a	b	N
1	-0.6587*	2.3506	-0.032	27
2	-0.7332*	3.1641	-0.0405	25
3	-0.7437*	3.8625	-0.1056	27
4	-0.7713*	3.8625	-0.0619	25

r - correlation coefficient

* - significant at 0.01

Values of a and b for the equation $Y = a + bX$

Y = unconfined soil strength (kg/cm^2)

X = surface moisture content (%)

N = sample size

centimetres. The volumetric creep over a 1 cm section of the controur was given by this value in cm^3/cm. Measurements of the amounts of creep at the surface were also made to enable comparison with other studies where this was the only measurement made. The results of these computations are shown in Table 18.

The form of the velocity profile in all cases where movement occurred indicated that the rate of shear increased to maximum at the surface as required by the theories of Davison and Culling. No indication of a decrease in the rate of shear towards the surface was seen.

While the original 30 tubes were positioned randomly the fact that only 14 could be used in the analysis makes the results of extrapolation very doubtful. However, an attempt to derive a meaningful estimate of soil creep has been pursued.

The mean of all the measured rates was 3.29 cm^3/cm. Assuming a constant rate for the whole year the annual rate was given as 3.95 $cm^3/cm/yr$. The influence of some controls of soil creep was analysed, and although there was a great amount of variability in the data some relationships were obtained. The most important factor affecting the movement of the ¼ inch PVC tubing was shown to be the angle of slope. Schumm (1964) has demonstrated a close correlation between the angle of slope and the logarithm of marker movement, described by the equation:

Table 18

Volumetric and Surface Movement of ¼ inch PVC Tubes

Tube Number	Volumetric Movement cm^3/cm	Surface Movement cm
1	0.0	0.0
5	1.61	0.5
6	4.84	0.75
9	1.29	0.7
11	2.64	2.05
13	4.13	1.2
14	2.84	1.95
16	2.51	1.55
18	2.35	1.2
22	0.0	0.0
25	3.74	1.9
26	8.77	2.65
28	7.74	3.4
30	3.93	1.1

$$\log_{10}Y = 0.017X - 1.36 \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where: X = angle of slope in %

Y = marker movement in feet.

For the same data Kirkby (1964) suggested a best fit line:

$$Y = 2.56 \sin^2\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where: θ = angle of slope in degrees.

Kirkby's equation, besides giving a good fit, also gave the rate of movement as zero for level ground, which was desirable from a theoretical viewpoint. For the Chilton Valley data the best fit line was:

$$Y = 11.5856 \sin^2\theta + 0.9513 \quad \ldots\ldots\ldots \quad (3)$$

where: Y = creep rate in cm^3/cm.

θ = angle of slope in degrees.

The correlation coefficient for this relationship was only 0.4171. For the best fit line through the origin

$$Y = 13.32 \sin^2\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

the correlation coefficient of 0.4168, was very little different.

The amount of creep measured was also correlated with variations in vegetation cover and a weak negative relation revealed. The multiple correlation coefficient of the measured creep against the percentage vegetation cover and $\sin^2\theta$ was 0.4606, so that only 21.46% of the variation of creep rates was explained by these variables.

Using equation (4) in combination with the frequency of slopes within the sampled area, a more accurate measure of creep was derived. The distribution of slopes within the valley is shown in Figure 13. This distribution is markedly bimodal and probably consists of two normal populations; the valley side slopes (which Strahler (1950) has shown to be normally distributed) and the valley bottom slopes. For the midpoint of each class the creep rate was derived and weighted according to frequency. Summation of these rates gave an average rate of 3.02 cm^3/cm for the ten month period which represents a rate of 3.62 $cm^3/cm/yr$.

For comparison with these figures the results obtained by Caine (1963) were converted to cm^3/cm. For a 19^o slope the rate of soil movement in the Lake District varied between 17.7 and 32.6 cm^3/cm for an eight month period, while on sites of 15^o movement ranged from 10.3 to 40.0 cm^3/cm. The corresponding rates for the Chilton Valley are 2.2 and 1.7 cm^3/cm respectively. However, the Lake District sites were unvegetated. Even so the rates for unvegetated sites in the Chilton Valley (1.61, 8.77 and 7.74 cm^3/cm) were still considerably smaller.

The only other results (to the author's knowledge) expressed as volumetric creep are those of Young (1960 and 1963) and Kirkby (1965), but comparison with these results would not be valid since both Young and Kirkby used Young Pit with nails for markers.

Most measurements of soil creep and similar processes have been presented in terms of the movement at the surface.

The relation between the movement at the surface and the angle of slope was also investigated and results proved to be slightly less significant. The best fit equation was:

$$Y = 3.918 \sin^2\theta + 0.5615 \quad \ldots\ldots\ldots\ldots \quad (5)$$

where: Y = surface movement in cm.

θ = angle of slope in degrees.

To enable comparison with other studies this was converted to feet/year, and this gave:

$$Y = 0.1541 \sin^2\theta + 0.0221 \quad \ldots\ldots\ldots\ldots \quad (6)$$

where: Y = surface movement in feet/year.

The results of some other studies are presented in Table 19, while the relation between measured rates and angles of slope for these studies is shown in Figure 14. For Schumm's data from West Colorado (1964), both Schumm's and Kirkby's best fit lines are shown. The Chilton Valley results appear to fit between the large movements recorded in sub-arctic and periglacial areas by Jahn (1960), Rapp (1960). Washburn (1962), and Caine (1963) and also in a semi-arid area by Schumm (1964), and the much slower rates recorded under temperate conditions and also in some semi-arid regions by Emmett (1965) and Leopold, Emmett & Myrick (1966).

Discussion. While the sparseness of the data makes this part of the analysis somewhat unsatisfactory, some results have been obtained.

That the form of the velocity profile of soil movement is similar to that proposed by Davison and Culling, rather

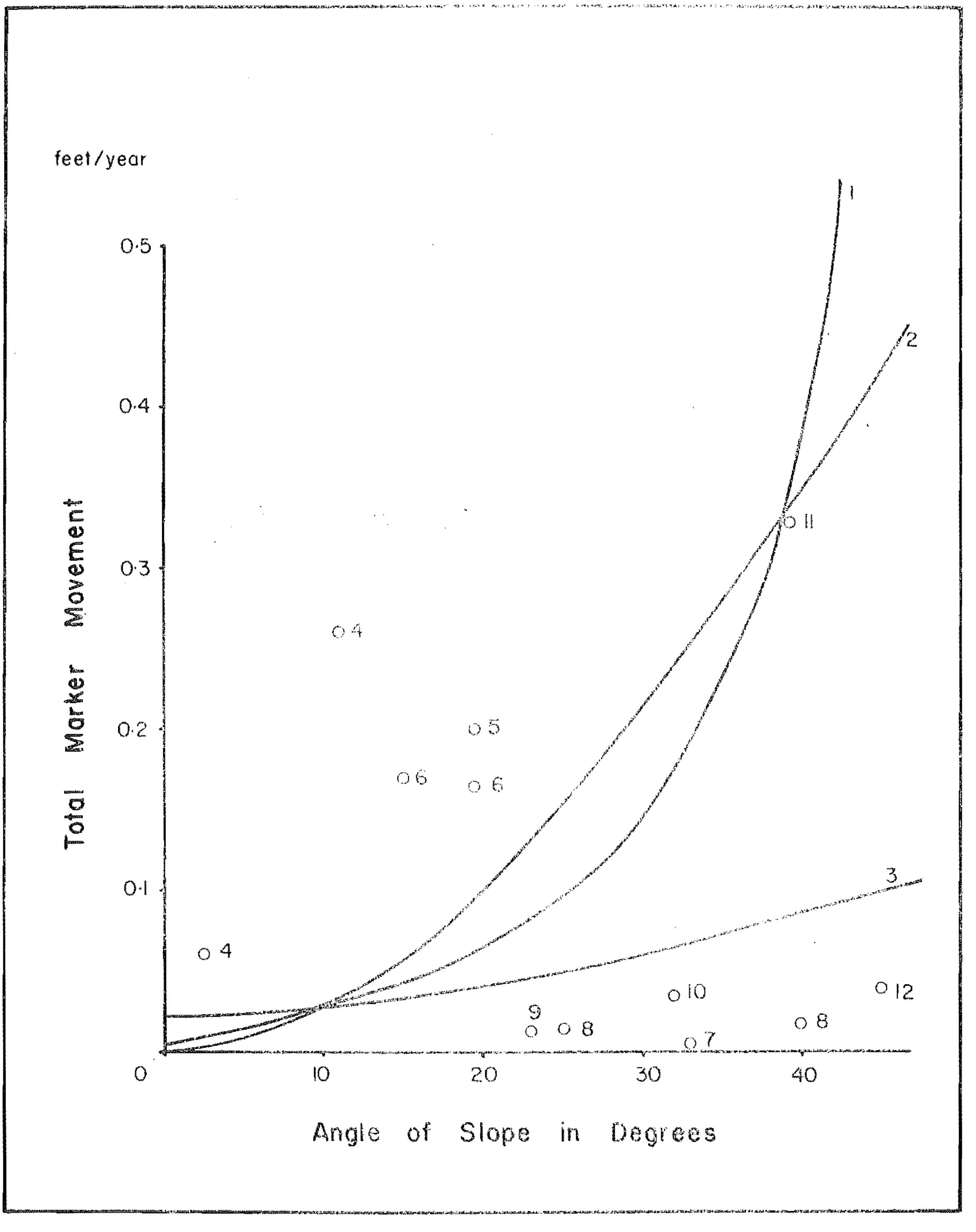
Table 19

Results of Previous Measurements of Mass Movement

Author	Location	Slopes (degrees)	Average Movement (ft/yr)	Processes
Young (1958)	Pennines	26	0.001	Soil creep
_____ (1963)	Derbyshire	25-30	0.0028	Soil creep
Everett (1962)	Alaska	-	0.065	Creep and solifluction
Washburn (1962)	Alaska	19	0.2	Solifluction
Schumm (1964)	Colorado	30	0.213	Creep
Caine (1963)	Lake District	19	0.225-0.275	Creep
		15	0.133-0.375	Creep
Emmett (1965)	Mexico	40	0.017	Creep
		25	0.017	Creep
	Forsaken Gully (Wyoming)	32	0.036	Creep
	Santa Fe (N.Mexico)	23	0.012	Creep
Leopold, Emmett & Myrick (1966)	N.Mexico			
	Slopewash Tributary	45	0.017	Creep
	Coyote C. Arroyo	-	0.017	Creep

Figure 14. The relation between slope movement at the surface and angle of slope for this and other studies.

1. Schumm (1964) (Schumm's best-fit line)
2. Schuum (1964) (Kirkby's best-fit line)
3. Chilton Valley
4. Jahn (1960)
5. Washburn (1962)
6. Caine (1963)
7. Young (1960)
8. Emmett (1965) New Mexico
9. Emmett (1965) Wyoming
10. Emmett (1965) Sante fe, New Mexico
11. Rapp (1960)
12. Leopold, Emmett & Myrick (1966)



feet/year
Total Marker Movement
0·5
0·4
0·3
0·2
0·1
0
10
20
30
40
Angle of Slope in Degrees
1
2
3
4
4
5
6
6
7
8
8
9
10
11
12

than that of Kirkby, seems clear. However, this may be a reflection of the processes involved, since Kirkby allows that freezing and thawing of soil moisture may produce the velocity profile suggested by Davison. This is clarified in the next section.

Some reasons for the differences in the amounts of soil creep measured in the Chilton Valley to that measured elsewhere may be suggested. Most investigations in higher latitudes have demonstrated much greater movements which are apparently caused by the more severe climates and lack of vegetation cover. The much greater rates recorded by Schumm (1964) may also be due to the existence of a sparser vegetation cover. The reasons why the Chilton Valley apparently has greater rates of movement than some semi-arid areas is not completely clear. One possible cause is that freezing of the soil moisture may not be important in the semi-arid areas. It is also possible that different methods of measuring movement have affected the comparability of the results. Both Emmett (1965) and Leopold, Emmett & Myrick (1966) used 10 inch pins which may not have reflected the correct amount of movement at the surface. Leopold, Emmett & Myrick give the tilts of the pins used as 1.4^{o}/yr (Slopewash Tributary) and 1.7^{o}/yr (Coyote C. Arroyo). These figures differ very little from the average of all T-bar tilts (in the Chilton Valley) of 1.5^{o} for the ten month period.

CAUSES OF SOIL CREEP

The basis for the investigation of the causes of soil creep was the use of correlation between climatic variables and short term measurements of mass movement.

Results

Since no movement was detected by the ¾ inch PVC tubes over the whole period, the inclinometer was of no value as an indicator of short term changes. Consequently this section of the investigation relied solely on the results of the T-bar measurements, though some inferences regarding the causes of soil creep can be made from the movement of the ¼ inch PVC tubes. Freeze-thaw measurements were obtained from ground thermistors and hence no results were available for Site 2. The records of frost heave are shown in Figure 15.

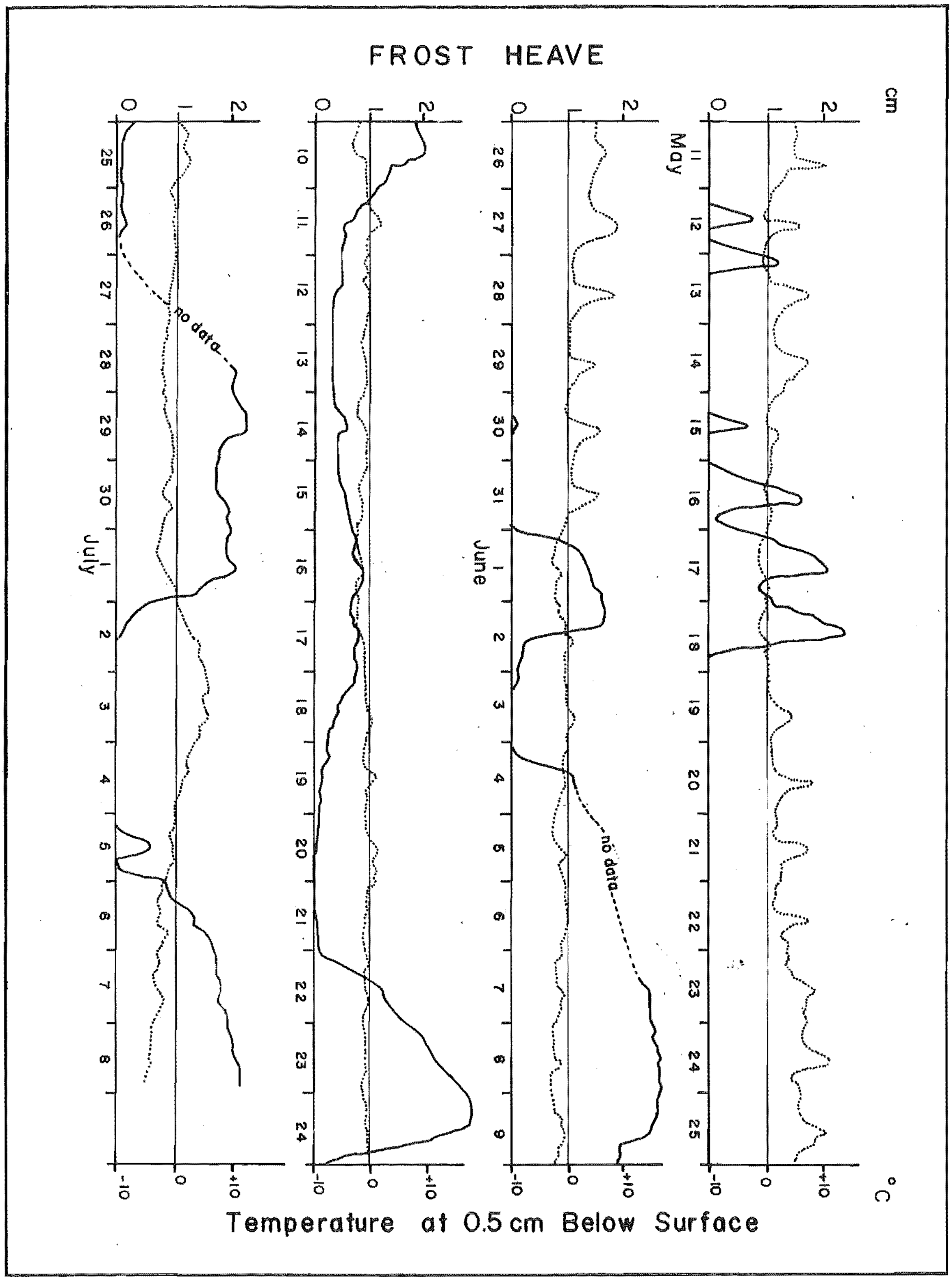
Correlation analysis of soil moisture content and various preceding periods of rainfall and radiation showed that, in all cases the rainfall and radiation that occurred in the 84 hours preceding sampling had the most significant influence on moisture content. For the four sites over 50% explanation of the variation of the moisture content from 0 - 3 cm was achieved using rainfall and radiation in the preceding 84 hours with logarithmic transformations of the data. The following prediction equations resulted:

$$\log_e M_1 = 0.0743 \log_e Rl - 0.0033 \log_e Rn + 4.0271 \quad \ldots.(7)$$

$$\log_e M_2 = 0.0653 \log_e Rl - 0.0022 \log_e Rn + 4.0708 \quad \ldots.(8)$$

$$\log_e M_2 = 0.0844 \log_e Rl - 0.0026 \log_e Rn + 3.3316 \quad \ldots.(9)$$

Figure 15. Records of frost heave. The heavy line shows the frost heave recorded and the dotted line the temperature at 0.5 cm below the surface approximately 2 metres away.



FROST HEAVE
cm
May
June
July
no data
no data
°C
Temperature at 0.5 cm Below Surface

$$\log_e M_4 = 0.0481 \log_e Rl - 0.0025 \log_e Rn + 3.9933 \quad \ldots (10)$$

where: M_n = % moisture content at surface of Site n.

Rl = rainfall in the preceding 84 hours in cm.

Rn = radiation in the preceding 84 hours in cal/cm^2.

Correlations between moisture content of samples from 7.5 - 10.5 cm and 15-18 cm and all periods of rainfall and radiation were much less satisfactory and no attempt was made to reconstruct a soil moisture record for these depths.

Analysis

The analysis of the short period movement consisted of correlating measured tilt for periods longer than a week with accumulated moisture content and the number of freeze-thaw cycles. Accumulated moisture content was obtained by adding all the increases in moisture content (derived by using Equations 7, 8, 9 and 10) for a given period.

In this analysis the response to T-bars to expansion and contraction of soil was considered in the simplest terms. A direct cause and effect relationship was assumed. Kirkby (1965) has measured and described two components of soil creep; long term and short term. Short term creep is that movement associated with expansion and contraction of the soil. An increase in moisture content, for example, would probably cause a short term downhill (positive) component of creep. Long term movement, however, was seen as the residual of these short term forces. Hence several cycles of moisture change could cause a small downhill movement due to the action of gravity. The length of the period dividing these two types of movement was arbitrarily placed by Kirkby at two weeks. In this study the amount of short term data was too small to allow investigation of the short term changes, and the analysis was restricted to long period changes here considered to occur over periods longer than one week. This may have some effect on the analysis of causes since the short term component cannot be allowed for.

As there was considerable variability in the results, the average movement recorded at each site was used in most correlations. However, the T-bars were of different lengths, and though no systematic relation between the amount of movement measured and the length of T-bar was revealed, the four smallest T-bars (2 of 20 cm and 2 of 25 cm length) were used in further analysis.

The correlation coefficients derived in this analysis are shown in Table 20. These showed that for the whole period accumulated moisture content was nowhere positively correlated with tilt but that the number of freeze-thaw cycles was important at Sites 1 and 3. Because of this the period was split into two segments; one affected by freeze-thaw and another in which freezing did not occur. Correlation coefficients of tilt against the number of freeze-thaws were increased at the three sites when only winter was considered. The effect of accumulated moisture content when the summer period was considered was still not strong. Only at Site 3 was there a reasonable correlation, which was just below the 0.1 significance level (mainly because of the small

Table 20

Causes of T-bar Movement

Site	Accumulated moisture		Freeze-thaw cycles	
	T_A	T_B	T_A	T_B
Whole period (N = 21)				
1	-0.0743	-0.103	0.4685**	0.4053*
2	-0.0937	-0.1852	______	______
3	-0.1067	-0.1072	0.7463***	0.6798***
4	0.166	-0.2464	0.0456	0.1077
Winter (N = 11)				
1	-0.1171	-0.167	0.5192*	0.4548
2	0.1625	0.0944	______	______
3	-0.3165	-0.0651	0.7785***	0.7348***
4	0.4625	-0.1817	0.3574	0.4786
Summer (N = 10)				
1	0.1836	0.1423	______	______
2	-0.0404	-0.184	______	______
3	0.5219	0.2609	______	______
4	0.0037	-0.4084	______	______

Correlation coefficients of T-bar tilt against accumulated moisture content and number of freeze-thaw cycles.

T_A - all T-bars, T_B - four shortest T-bars

N - number of observations

Significance levels: * $p = 0.1$; ** $p = 0.05$; *** $p = 0.01$.

sample size).

Discussion

Some reasons for the variations of these correlation coefficients may be suggested. It is evident that significant correlations were found only where there was a definite downhill tilt measured. At Sites 2 and 4 the short term creep associated with expansion and contraction of the soil was probably as large as the long term residual component. For Sites 1 and 3 the short term creep associated with freeze-thaw probably did not affect the results since the soil had usually thawed when measurements were made at these sites. The record of frost heave, however, shows that near Site 4 the soil remained frozen for long periods in mid-winter when this site was in the shade all day for several days.

The importance of freezing and thawing of the soil moisture in causing soil creep seems clear from this analysis. Soil moisture changes may have some effect as shown by the analysis of the summer period, but its importance relative to that of freezing and thawing, is minor. This may help to explain the lack of relation between those site features that may have affected volume changes of soil with moisture changes (such as effective size and silt-clay content) and the amounts of movement recorded. The action of freezing and thawing in causing soil creep is also suggested by the form of the velocity profiles which that movement took place only in the top 5 cm, where the effects of freeze-thaw are concentrated.

CONCLUSION

Investigations of soil creep show that it occurs at a rate of 3.6 cm^3/cm/yr or 1.6 cm/yr at the surface. Both vegetation cover and the angle of slope have some control on the amounts of creep occurring. These creep rates are much smaller than rates recorded in arctic and periglacial areas, and may be slightly larger than rates in more temperate areas, though different measurement techniques cast some doubt on the validity of the second comparison. The form of the velocity profile of soil creep corresponds more closely to the theories of Davison and Culling than to Kirkby's theory. However, this does not disprove Kirkby's theory since he allows that freezing and thawing of soil moisture may have special effects, and the analysis suggests that this is the most important cause of creep in this area.

CHAPTER 5 SCREE INVESTIGATIONS

The division of the consideration of the field measurements into the two sections of soil creep and scree investigations is made more for convenience than for absolute accuracy. Such a distinction is based more on methods of measurement than on a difference in the processes measured. The movements measured are not considered as true talus creep but as transitional between this and soil creep (Sharpe, 1960, p.30). In this study screes are distinguished from talus slopes as defined by Rapp (1960b, p.4), and given the more general connotation of unvegetated areas of slopes between 15° and 40° (but usually about 30°) and mantled by poorly sorted material ranging from block size to clay. The measurements discussed in this chapter are quite comparable to other scree investigations.

If a scree slope is considered as a system the movements of scree material can be characterized as either input, transfer, or output. This study is concerned only with the second of these; with measuring the rate of movement of material on the surface of the scree.

THEORIES OF SCREE SLOPE MOVEMENT

Most general theoretical considerations of scree development have dealt with the relationships between scree forms and the manner of bedrock retreat, the volume of the material in the scree, and only rarely with the processes which cause movement of scree material.

Early investigations by Moseley (1869) and Davison (1888) demonstrated that diurnal changes of temperature were capable of causing movement of various types of blocks resting on inclined surfaces. Sharpe (1938) included amongst causes of scree movement:

(1) alternate freeze and thaw of ice in the interstices of the rock waste,

(2) diurnal temperature change,

(3) prying and growing of roots and swaying of trees in the wind,

(4) disintegration of rocks followed by removal by water and settling.

Fisher (1952) suggested for a scree slope on Mount Bailey, in the Cass Basin, that scree movements were greatest after heavy snowfalls and wet weather, and that daily temperature change was also important. More recently Scheidegger (1961) and Kirkby (1965) have derived theoretical creep rates due to temperature changes on "dry" screes.

FIELD INVESTIGATIONS

Fabric Analysis

Only two samples were measured and these were chosen very subjectively. Sample A was from an accumulation of particles (mostly longer than 5 cm) near the bottom of the scree, while Sample B was from what looked to be a more "mobile" portion with larger particles scattered around on the finer subsoil.

Results. The results of the fabric measurements are shown graphically in Figure 16 while the analysis is summarized in Tables 21 and 22. The summary of the two-dimensional analysis is presented (along with other orientation indices) to enable comparison with the three-dimensional analysis results, and with the results of other studies. In the two-dimensional analysis all vector magnitudes were significant at the 0.05 level but the magnitudes for inclination were larger than those for orientation indicating a "girdle" form also shown on the fabric diagrams. (Pettijohn 1957, p.77).

Three-dimensional analysis is considered to give more valid results since the full 360° of orientation is used in combination with inclination. Rotation of the reference plane by 90° about a line normal to the slope direction gave a better estimate of the vector mean for Sample A but not for Sample B.

Discussion. This analysis indicates a strong tendency for particles on the scree slopes under consideration to have a preferred orientation in the slope direction and an inclination slightly less than the angle of slope. This type of fabric pattern has also been observed by Rapp (1960a), Andrews (1961) and some other workers. Cailleux & Tricart (1966) have tabulated the results of some investigations of talus fabric (Table 23). However, comparison of these results with those of the Chilton Valley indicates stronger preferences for orientation with the slope direction in the Chilton Valley. Chandra (1967) showed a tendency for down-

Figure 16. Fabric diagrams of scree surface particles above Site 3.

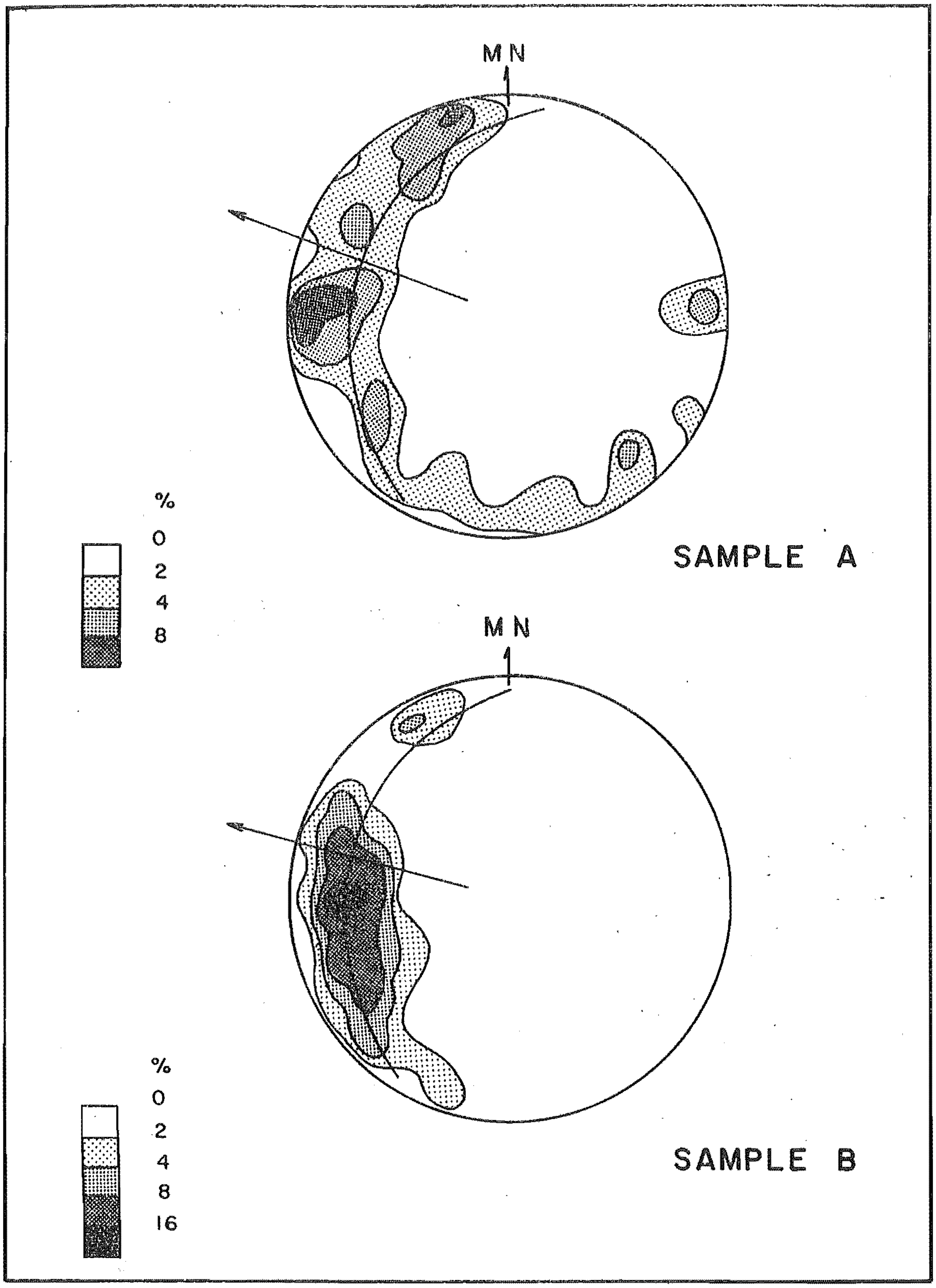

MN
%
0
2
4
8
SAMPLE A
MN
%
0
2
4
8
16
SAMPLE B

Table 21

Two-Dimensional Fabric Analysis

Sample	A	B
Orientation		
Vector mean (degrees)	30	86
Vector magnitude (R)* (%)	26.43	66.36
χ^2**	34.5	72.72
Parallel Index (Pa)[1]	68	80
Strict Parallel Index (Ps)[2]	50	65
Slope direction (degrees)	110	105
Inclination		
Vector mean (degrees)	14	23
Vector magnitude (R)* (%)	87.5	95.2
χ^2**	164.47	258.5
Slope angle (degrees)	25	27

* for N = 50, p = 0.05 at R = 24%.

** for number of classes = 18, p = 0.05 at χ^2 = 26.3.

1 - % particles within 45° of slope direction.

2 - % particles within 30° of slope direction.

Table 22

Three-Dimensional Fabric Analysis

Sample	Orientation (degrees)	Dip (degrees)	Vector magnitude (R)* (%)	Estimate of precision (K)**
Horizontal reference plane				
A	115	30	57.66	2.315
B	85	26	91.2	9.736
90° reference plane				
A	117	16	74.46	3.837
B	119	30	85.5	6.742

* for $N = 50$, $p = 0.05$ at $R = 11.39$

** $k \geqslant 3$ indicates approximation to a spherical normal distribution.

Table 23

Other Measurements of Fabric on Talus Slopes[1]

Author	Location	Slope (degrees)	Parallel index Pa (%)	Strict parallel index Ps (%)
Cailleux	France Serenne	30-37	67	
Cailleux	Poland Zakopane	30-35	71	
Cailleux	France Oredon (H.P.)	30-35	77	52
———	Belgium	29-31	60	
Poser	Defile de la Salm Germany	30-38	69	49
Tricart	Austria Brand	24	30	28
Tricart	Austria Brand	32	60	44
Tricart	Austria Brand	32	30	22
Hamelin	France St.Sorlin	35	66	

[1] after Cailleux & Tricart (1966)

slope orientation of particles on scree at Porters Pass, Canterbury. However vector magnitude was significant for only 7 out of 15 samples. Caine (1967) has cast some doubt on the validity of previous observations of this type of fabric pattern by suggesting that the evidence used was insufficient. While the evidence in this study is also not very strong, because of the small sample size, the methods used are similar to, and as rigorous as, those recommended by Caine. The difference in fabric pattern and directional trends between the material of Tasmanian talus slopes and the Chilton Valley screes is striking. These differences could be attributed to mean size and sorting contrasts. Caine has also related the generally isotropic fabric pattern found on Tasmanian talus to the accumulation process important in talus formation. The strong preferences in the orientation and inclination of the Chilton Valley scree material would, however, indicate that movement of material is occurring on these slopes.

Rates of Scree Movement

Results. Table 24 summarizes the results of the scree measurements for the whole period, while the amounts of movement are shown graphically in Figure 17.

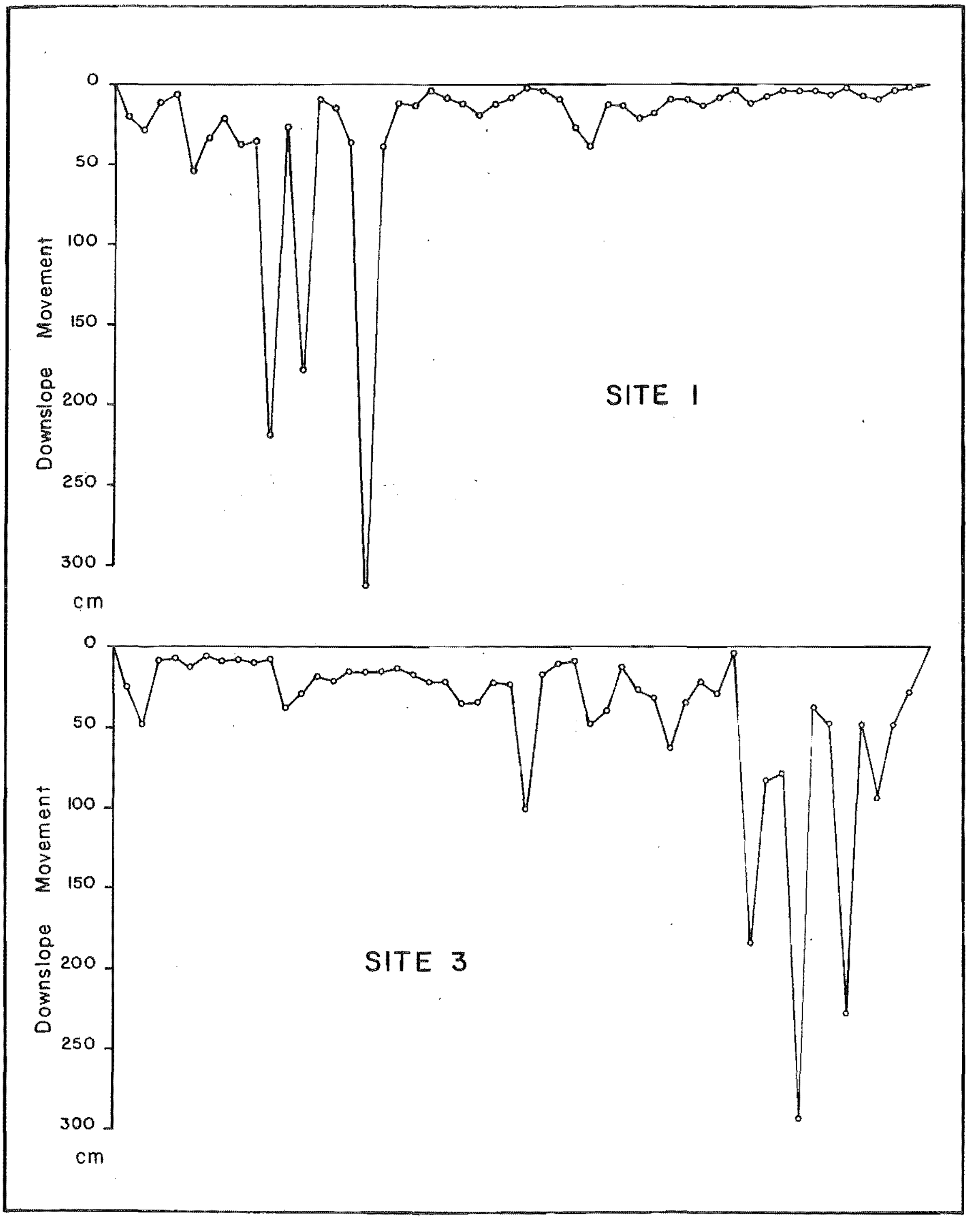
Analysis. The problem of how to treat mass movement data of this nature has been discussed recently by Caine (1967). He has pointed out the lack of a standard method of presenting the results of a series of measurements of surface movement.

Table 24

Rates of Scree Movement - Whole Period

Site	Arith-metic mean (cm)	Median (cm)	$\bar{x}$ ($\log_{10}$)	Geom-etric mean (cm)	s ($\log_{10}$)	Range $\bar{x}$-s to $\bar{x}$+s (cm)
1	28.1	10.6	1.0757	11.91	0.5392	3.44 to 41.2
3	41.0	22.0	1.4135	25.91	0.4632	10.24 to 65.6

Figure 17. Movement of marked stones at the surface on Sites 1 and 3. The circles indicate the final position of 50 stones at each site.

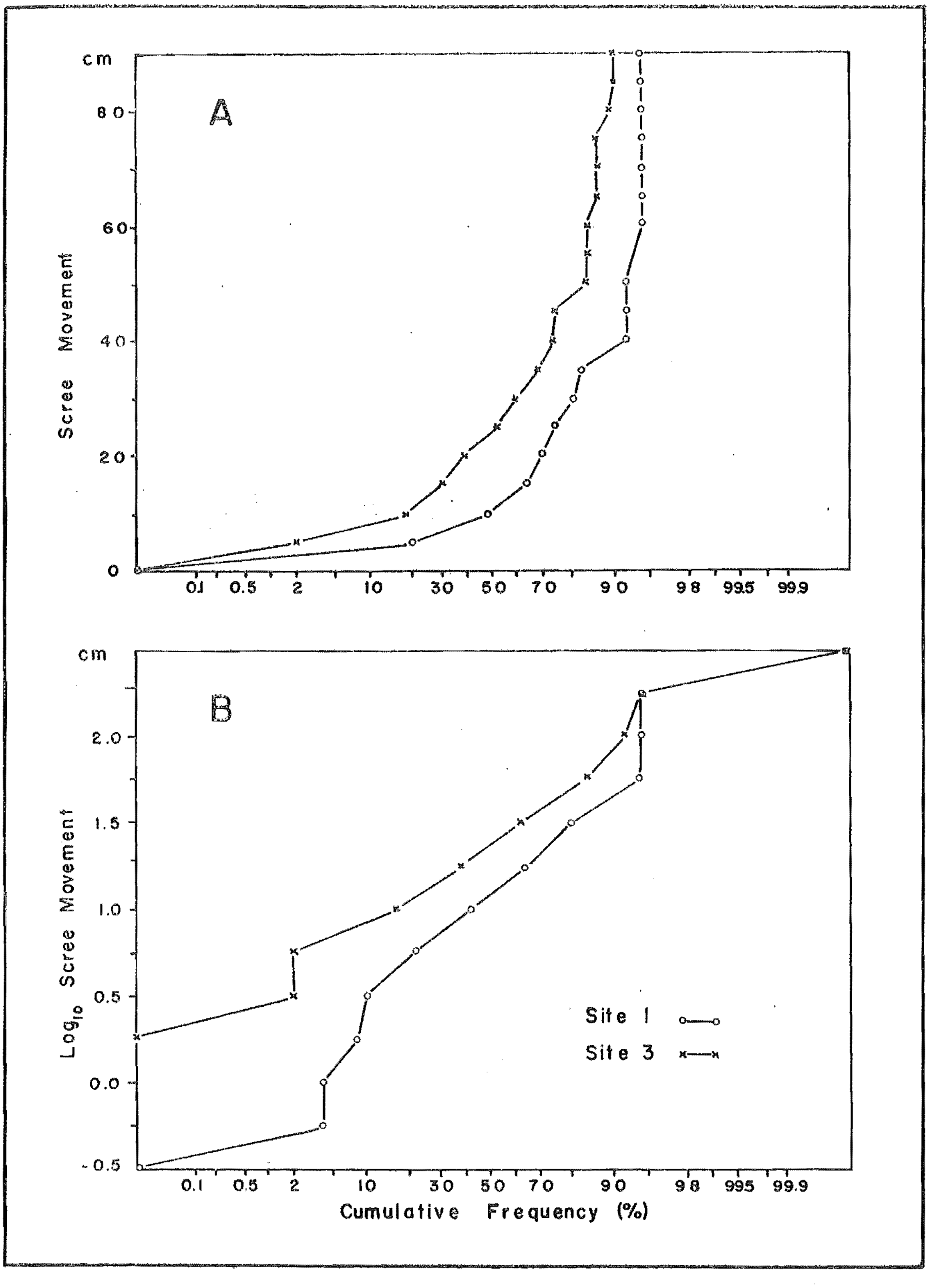


0
50
100
150
200
250
300
cm
Downslope Movement
SITE 1
0
50
100
150
200
250
300
cm
Downslope Movement
SITE 3

Some writers, such as Gradwell (1957), have used the arithmetic mean while others, recognising the skewed form of the distribution of movements, have used the median (Caine, 1963). The use of a logarithmic transformation is thought to normalize the distribution sufficiently to allow standard statistical methods to be used on it. Although χ^2 tests on the transformed data show that it is not perfectly normalized, the close approximation to normality in the $\pm 2\sigma$ range is certainly sufficient to allow analysis of variance. (Figure 18 shows the effect of the logarithmic transformation). The average movement of the sample is given by the geometric mean (the anti-logarithm of the mean of the transformed data) while the standard deviation of the transformed data is used as a measure of the range. Other previously used measures are included to allow comparison with other studies (Table 24). These were converted to a yearly rate and are shown along with other measurements in Table 25. (The following section suggests that this conversion will actually underestimate the rate since two winter months were not included in the measurement period.)

Discussion. This analysis shows an average rate of 14.3 cm/yr at Site 1 and 31.1 cm/yr at Site 3. These rates appear to be similar to those recorded in South Georgia by Smith (1960), but much greater than those of Rudberg (1964). However, the rate of scree movement in the Lake District measured by Caine (1963), is much greater than the median movement for the Chilton Valley. The results obtained by

Figure 18. Frequency distribution of scree movement (A) and $\log_{10}$ scree movement (B) on normal probability paper. A straight line would indicate a perfectly normal distribution. The lines for the logarithmically transformed data more closely approximate a straight line than the original data.



A
cm
80
60
40
20
0
Scree Movement
0.1
0.5
2
10
30
50
70
90
98
99.5
99.9
B
cm
2.0
1.5
1.0
0.5
0.0
-0.5
Log_{10} Scree Movement
Site 1
Site 3
0.1
0.5
2
10
30
50
70
90
98
995
99.9
Cumulative Frequency (%)

Table 25

Comparison with other Measurements of Scree Movement

Author	Location	Slopes (degrees)	Arithmetic mean cm/yr	Median cm/yr	Total range cm/yr
Gradwell (1957)	Molesworth (N.Z.)	11	16.5		
		2-5	2.5-7.5		
Rapp (1960)	N. Sweden	37			25-500
Smith (1960)	S. Georgia	21	47.0		
Caine (1963)	Lake District	15		12-18	
		25		45-50	
Rudberg (1964)	Swedish Lappland	10	0.1		0.0-0.5
		14	0.2		0.0-1.0
		15	0.1-1.6		0.0-3.0
		25	0.5-0.7		0.0-2.8
Present study	Chilton Valley	27	33.6	12.7	0.5-322.0
		27	49.5	26.4	3.0-334.0

Gradwell (1957), are not strictly comparable to those of the present study since his measurements were made on much gentler slopes.

Causes of Scree Movement

Results. Unfortunately a logarithmic transformation could not be applied to the short term measurements because of the large number of zero movements. The arithmetic mean did not reflect the true situation either since a large movement by one stone could greatly affect the mean. Consequently, the median movement was used as a measure of the average movement over short periods. The median movement for each period is shown in Figure 19 which also shows the number of freeze-thaw cycles that occurred between measurements.

Analysis. The correlation between the number of freeze-thaw cycles and the median movement is apparent from Figure 19. As well as this, an analysis of variance was performed using logarithmic transformation of the total movements that were and were not affected by freeze-thaw. The 23 weeks of summer measurements were first converted to the equivalent of 12 weeks since there were only 12 weeks of winter records. The results of this analysis are shown in Table 26.

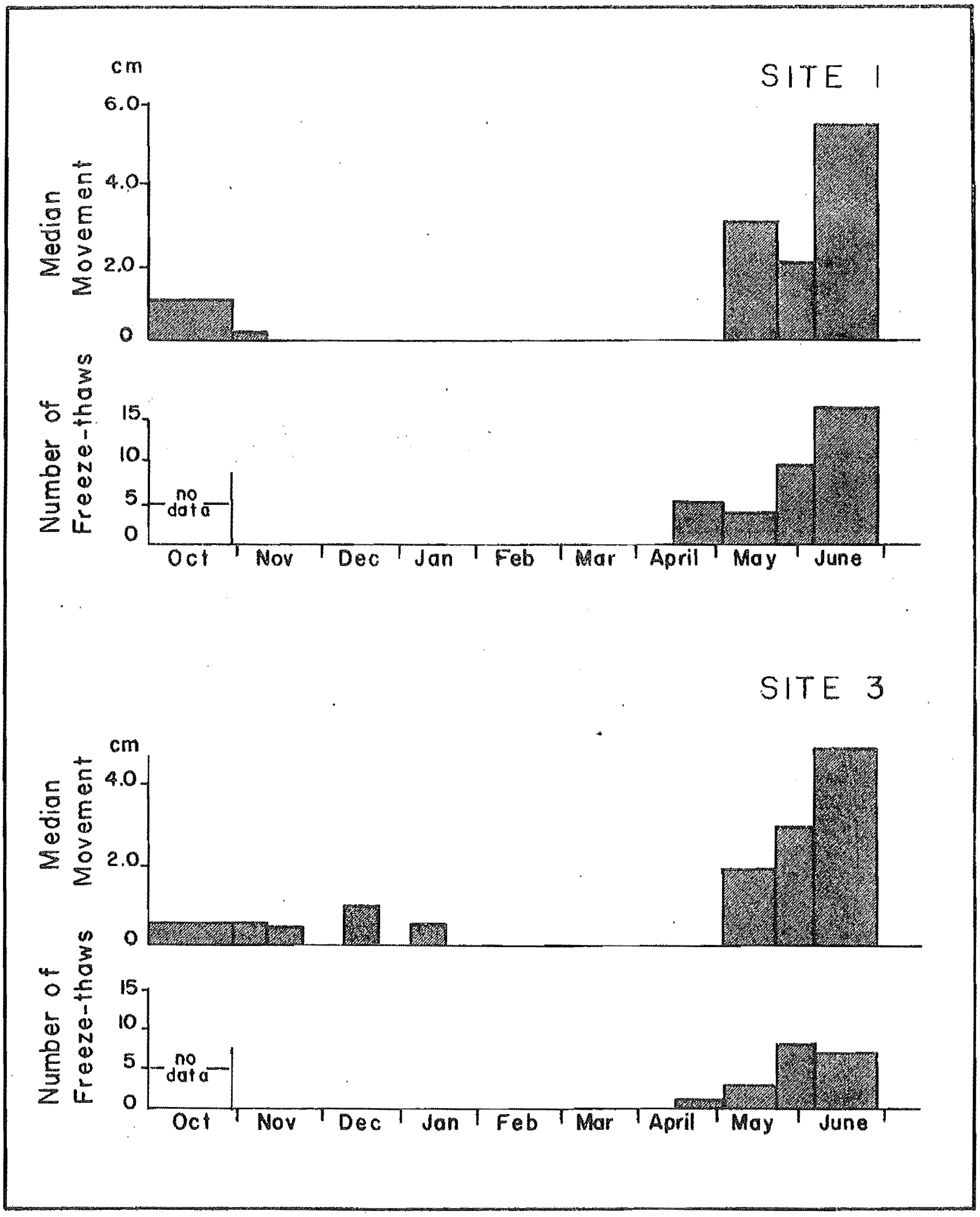
Two different types of movement could be distinguished from the short period measurements of scree movement:

(1) creep

(2) individual rolling or sliding.

An arbitrary figure of 20 cm/2 week period was taken as the

Figure 19. Short period movement of scree particles and numbers of freeze-thaw cycles.



SITE 1
cm
6.0
4.0
2.0
0
Median Movement
Number of Freeze-thaws
15
10
5
0
no data
Oct
Nov
Dec
Jan
Feb
Mar
April
May
June
SITE 3
cm
4.0
2.0
0
Median Movement
Number of Freeze-thaws
15
10
5
0
no data
Oct
Nov
Dec
Jan
Feb
Mar
April
May
June

Table 26

Analysis of Variance - Scree movement in Summer and Winter

Site	d.f.	Between mean square	Within mean square	F	Significance (%)
1	1/98	13.6645	0.3229	42.315	99.99
2	1/98	22.8158	0.7079	32.2303	99.99

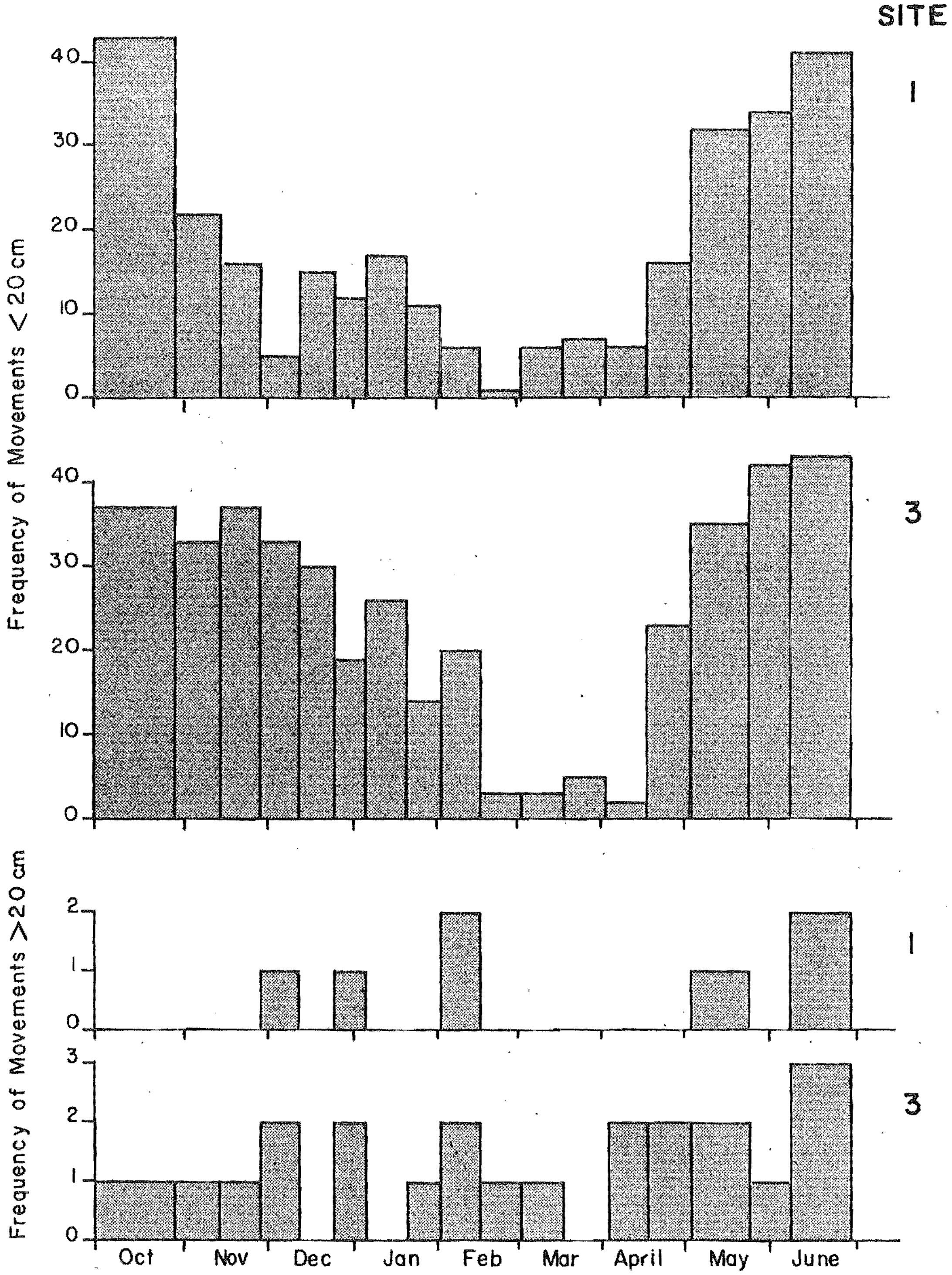
boundary between these two types of movement. The frequency of occurrence of these movements is shown in Figure 20. The smaller movements occurred more often in the winter period though the stones on Site 3 apparently took longer to settle. Except for this settling period there was no period in which a large number of the longer movements occurred. This suggests that smaller movements were caused by freeze-thaw (which supports previous analysis) while no definite cause can be stated for the longer movements. These movements were more characteristic of Site 3, where larger particles rested on a fine and often well compacted subsoil. This surface was much more conducive to rolling of single particles than one consisting entirely of larger particles. A possible cause (but one which cannot be substantiated) is the action of animals, especially sheep.

Discussion. There seems little doubt that on the scree slopes investigated the main climatic factor causing movement was the freezing and thawing of the interstitial moisture. This is at variance with the causes suggested by Fisher (1952) for a scree on Mount Bailey in the Cass Basin. The causes suggested here however, do agree well with those proposed by Caine (1963) for movement of surface material in the Lake District, although the sliding of stones on the thawed surface was not observed in the Chilton Valley.

Conclusion

Fabric analysis of two scree samples indicates a strong tendency for an upslope imbrication pattern, which suggests

Figure 20. Frequency of occurrence of "short" and "long" movements of scree particles.


SITE
1
3
1
3
Frequency of Movements < 20 cm
Frequency of Movements > 20 cm
Oct
Nov
Dec
Jan
Feb
Mar
April
May
June

that movement is occurring on these slopes. The rate of scree movement measured over the whole period compares well with measurements made by Smith (1960), is less than that recorded by Caine (1963) and considerably more than the rates reported by Rudberg (1964). The most important cause of this movement is the freezing and thawing of interstitial moisture.

CHAPTER 6 THE GEOMORPHIC SIGNIFICANCE OF SLOW MASS MOVEMENT

In this chapter an attempt is made to estimate the significance of slow mass movement processes in relation to some other processes. The erosional processes occurring in the Chilton Valley are thought to be:

(1) talus creep

(2) soil creep

(3) slope wash

(4) debris flows

(5) removal of salts in solution

(6) stream erosion

(7) wind erosion

(8) rockfall

Of these only the first four have been measured, the first two in this study, slope wash by Soons (1966) and debris flows by Brundall (1966). Even with these four processes there is the possibility of duplication in measurement, especially with respect to slope wash and soil creep which can be distinguished by definition but not very easily in measurement.

Here, the rates of movement associated with slope wash and debris flows are first discussed and this is followed by an attempt to convert measurements of different processes into the same units by a method suggested by Jackli (1957) and used by Jackli and Rapp (1960a). The problems of measurement and extrapolation from very small samples are present throughout this section. However, the analysis is still considered worthwhile, if only to provide hypotheses for further work.

MEASUREMENTS OF OTHER PROCESSES

Slope Wash

Slope wash measurements have been made over a period of two years by Soons (1966). Seven run-off plots measuring 9 ft x 4 ft 7½ inches were used. The volume of material removed from the plots can be expressed in the same terms as the soil creep results. Thus, a mean volumetric movement of 2.43 $cm^3/cm/yr$, with a range of 0.12 to 12.34 $cm^3/cm/yr$, has been recorded. This is considerably greater than the rates measured by Young (1958) and Kirkby (1965), who used soil tins with the lip of the tin two inches below the soil surface and with no restraint on upslope run-off. Young derived a rate of 0.084 $cm^3/cm/yr$ and Kirkby one of 0.089 $cm^3/cm/yr$. Both of these rates are less than the minimum recorded in the Chilton Valley, the contrast probably being due to different conditions in the A_o horizon and perhaps to different rainfall regimes. If anything the run-off trays used in the Chilton Valley (set at the surface) would minimize soil wash relative to the other studies.

Schumm (1956a and 1964), Emmett (1965) and Leopold, Emmett & Myrick (1966) have measured amounts of slope wash erosion by observing the lowering of the surface around graduated stakes. These rates can be compared to Soons' calculations of surface lowering (Table 27). Schumm's measurements in West Colorado showed no net stake exposure though the seasonal variations were of the same order of Soons' results. The measurements of Schumm (1956a), Emmett (1965) and Leopold, Emmett & Myrick (1966), are much greater than those for the Chilton Valley.

Debris Flows

Brundall (1966) measured the volumes of gullies and flows in the Chilton Valley and also attempted to date the occurrence of these flows from aerial photographs and old ground photographs. However he did not link these to estimate the rates of erosion associated with these processes.

Some of the incipient gullies were dated as pre-1870 but all of the flows studied apparently occurred after 1930. The volume of material in the flows moved over a period of forty years is used here as an estimate of the rate of erosion. This may underestimate the actual rate since the volume of the gullies is six times that of the flows. The total volume of the two flows is given as 117,000 ft^3 or 3,300 m^3. It is possible to express the volumetric rate for a point at the junction of the erosional and depositional segments of these features. This is given by the distance moved multiplied by the average depth and divided by the number of years, or:

$$43{,}000 \text{ cm} \times 10 \text{ cm} / 40 \text{ yrs} = 107400.0 \text{ cm}^3/\text{cm/yr}.$$

Table 27

Measurements of Surface Lowering Rates

Author	Location	Rate (cm/yr)	Period of measurement (yrs)
Soons (1966)	Chilton Valley	0.0005-0.045	2
Emmett (1965)	Aching Shoulder (N. Mexico)	0.45	1
	Forsaken Gully (Wyoming)	1.0-1.5	1
	Last Day Gully (Wyoming)	0.7	1
Schumm (1956)	Perth Amboy (N. Jersey)	2.5	2½
	W.Colorado	No net exposure	4
Leopold, Emmett & Myrick (1966)	Slopewash Tributary (N.Mexico)	0.23	5
	Coyote C. Arróyo	0.72	3

This very high value (compared to the values for creep and wash) is misleading since debris flows occurred on only 1.8% of the area of the valley and the value the maximum one within each debris flow.

COMPARISON OF PROCESSES

Method and Results

The method of comparing the effects of different processes was to convert the rate of movement measured to ton-metres (vertical) per year. This figure was computed by working out the volume of material involved (from the area affected and the average depth of movement), the weight of material (from the volume multiplied by the density), and this was then multiplied by the average movement and the sine of the average gradient. This computation is summarized in Table 28. Unfortunately, insufficient information was available for some processes. The results of the computations are presented in Table 29, and peculiarities in the derivation of the rate for each process are discussed below.

Soil Creep. The results of the volumetric analysis were used in the calculation of the rate for soil creep. The depth to which movement occurred was taken as 5 cm and the yearly rate as 3.6 cm^3/cm. This gave an average movement of the 5 cm layer of 0.7 cm. Bulk density measurements showed that the density of the material involved was about 0.7 $tons/m^3$.

Talus Creep. Extrapolation from the limited data was not very satisfactory. The movement was considered to occur

Table 28

Calculation of Erosion Rates

$$\cos\theta^* \times \underset{(m^2)}{\text{area affected}} \times \underset{(m)}{\text{average depth}} \times \underset{(tons/m^3)}{\text{bulk density}} \times \text{average movement} \times \sin\theta^*$$

$$= \underset{(m^3)}{\text{volume affected}} \times \underset{(tons/m^3)}{\text{bulk density}} \times \underset{(m)}{\text{vertical movement}}$$

$$= \underset{(tons)}{\text{mass}} \times \underset{(m)}{\text{movement}}$$

---

* θ is the average gradient in degrees.

Table 29

Amounts of Erosion by Different Processes

Process	Area affected (%)	Volume (m^3)	Density (ton/m^3)	Mass (tons)	Average movement (m)	Average gradient (degrees)	Total erosion (ton.m/yr)
Soil creep	70.7	3327.0	0.7	2229.0	0.007	25	6.60
Talus creep	20.2	952.1	1.5	1428.0	0.2	30	142.82
Slope wash	70.7	—	—	210.0	0.2	25	17.79
Debris flows	1.8	3313.0	1.0	3313.0	10.67	30	17684.2

mainly in the top 0.5 cm since the measurements referred to larger particles scattered about on the scree slopes. The screes were not of solid rock (density 2.7 tons/m^3) so a density value of 1.5 tons/m^3 was assumed. For the average movement a figure of 20 cm (derived from the scree investigations) was used.

Slope Wash. Soons (1966) gives sediment yield in terms of weight of material so that the volume of the material does not have to be computed. The average sediment yield from the run-off plots of 604.07 gm/yr represents a sediment contribution of 156.2 gm/m^2/yr. No measurements of the average movement of material was made and so it has been assumed to be 20 cm/yr.

Debris Flows. Since the material in the flows consists of both soil and larger particles its bulk density was taken as 1.0 tons/m^3. The average movement was derived by dividing the distance between the mid-point of the gully and that of the flow by the number of years under consideration. This gave a rate of 10.67 m/yr.

Sources of Error. Previous estimates of amounts of erosion have rarely included an estimate of the error involved. Usually a statement referring to the source of data (such as "rough estimate" or "exact measurement") is made. The error involved in making quantitative calculations of erosion rates stems from the following sources:

(1) measurement

(2) sampling

(3) extrapolation

The first of these can usually be estimated, the second stated on a probability basis provided the original sample was random, but it is very difficult to estimate the error involved in extrapolation.

The probable errors involved in the calculation of the soil creep rate are now considered. The estimated measurement errors for the operations outlined in Table 27 are shown in Table 30. The maximum relative error for the result of these computations may be derived by summing the individual errors (neglecting for the moment the sampling error). The derivation of the maximum relative error is considered in more detail in Appendix V. The sampling error is stated on a probability basis (Appendix V). In this enquiry the error was 45.8% at the 0.05 level, which indicates that the maximum relative error in the estimate of soil creep is considerably greater than 100%. To this must be added errors of extrapolation. The actual error may lie between zero and the maximum relative error but the aim must be to minimize the latter.

The error involved in the calculation of the talus creep rate has not been computed, but because of the extremely small sample it is likely to be larger than that of soil creep. Other errors have not been computed since the results were derived from other work.

In terms of the present results this is not encouraging but it does suggest a method likely to reduce errors

Table 30

Errors of Measurement in Derivation of Erosion Rates

Measurement	Estimated Error (%)
Area involved	10
Average gradient	10
Average depth	20
Density	15
Average movement	30
Average gradient	10

in further work. The simplest means of reducing the maximum relative error would be to increase sample size.

Discussion

The results in Table 29 indicate that debris flow is by far the most important erosional process in the Chilton Valley. However, Wolman & Miller (1960) note that the evaluation of the relative importance of different geomorphic processes in molding specific forms involves the frequency of occurrence as well as the magnitude of individual events. They suggest that the most important processes are those of moderate magnitude and frequency, rather than rare catastrophic events. In this study, however, the frequency of events if allowed for as an average rate of transport is used. The main problem is whether the period of measurement is long enough to allow the average to correctly represent the frequency of different events. For processes associated with a high frequency of particular climatic events (such as soil creep, talus creep and soil wash) a short study is probably sufficient. However, for catastrophic processes caused by infrequent climatic events a much longer period of study is needed for the average rate to correctly represent the frequency of events. Despite this uncertainty, it still appears that debris flow is the most important slope-forming process of those measured. This does not mean that debris flow is the most important process in terms of landform genesis since this process is probably related to the present epicycle of anthropogenic erosion (McArthur, 1964).

Comparisons of the effects of slope wash and soil creep are jeopardized by the lack of evidence on the average movement of material involved in slope wash. However, the volume of slope wash has already been shown to be less than that of soil creep, but it is possible that the concentration of movement at the surface and the greater downslope movement probably involved would allow a larger contribution in terms of ton-metres.

These rates can be compared to those in other studies. Table 31 presents the data for such a comparison. The results from the three areas have been converted to ton-metres/yr/km^2, because of the disparity in size of the areas concerned. In terms of unit area the Chilton Valley has smaller mass movement rates than Karkevagge but the Chilton Valley mudflows account for about four times as much erosion as those at Karkevagge. The Upper Rhine has a very much greater rate of erosion attributed to slow mass movement processes.

The rates of erosion caused by processes measured in this study can also be compared to the total amount of deposition represented by the volume of the fan at the bottom of the valley. Computation of the volume of the fan gave a result of 13,000,000 m^3 and assuming a density of 1.5 tons/m^3 the mass of the material in the fan was given as 19,750,000 tons (Appendix VI). The ton-metres needed to

Table 31

Comparison With Other Quantitative Estimates of Mass Movements

Process	Rate (ton-m/yr)			Rate/unit area (ton-m/yr/km^2)		
	Chilton Valley	North Sweden	Upper Rhine	Chilton Valley	North Sweden	Upper Rhine
Mudflows	17684.0	76,000	---	18745.0	4,225.0	---
Talus creep	142.8	2,700		151.5	150.0	
Soil creep	6.6		23×10^6	7.0		5,340
Total slow mass movements	149.4	8,000	23.7×10^6	158.5	445.0	5,510

form this fan (the vertical distance taken as the height difference between the mid-point of the valley and the fan) was given as 6,021,000,000 ton-metres. This represents a rate of 400,000 ton-metres/yr in the 15,000 years since deglaciation of this area (McArthur, 1964, p.16). As could be expected this rate is considerably larger than that of the measured processes. However, direct comparison between this rate and that of present processes cannot be made because of the incomplete data regarding these processes. The processes not considered, although shown to be important agents of denudation in other studies, would have had little effect on the volume of the fan (with the exception of stream action).

Measurement of the volume of the Chilton Valley by measuring the area of cross-sections and integrating over the length of the valley, shows that the volume of the valley is approximately thirteen times that of the fan. If the valley is assumed to be completely erosional (and this assumption cannot be substantiated), then it has certainly not been formed since the end of the last glaciation.

CONCLUSION

A comparison of some erosional processes in the Chilton Valley shows that the rate of slow mass movement processes is much smaller than that of debris flows. The volumetric rates of soil creep and slope wash are similar but slope wash probably causes more erosion in terms of ton-metres/yr. The rates of processes measured here are comparable with those measured in Northern Sweden but much smaller than those of the Upper Rhine. No comparison with the total amounts of erosion for these areas could be made because of insufficient data from the Chilton Valley.

The mean rate of deposition since deglaciation of this area is approximately 20 times that of the processes so far measured. This suggests that other processes may be important or more probably that rates of erosion and deposition have varied considerably since deglaciation.

CHAPTER 7 CONCLUSION

SUMMARY OF CONCLUSIONS

Although this study of slow mass movements in the Chilton Valley was limited by the problems of measurement some conclusions regarding these processes have been reached.

Soil creep occurs at a rate of 3.6 cm^3/cm/yr or 1.6 cm/yr at the surface, and this rate is comparable to rates measured in temperate areas but smaller than rates for arctic and some arid areas. The velocity profile of soil creep corresponds more closely to the theories of Davison and Culling, than that of Kirkby. This does not disprove Kirkby's theory, since he suggests that freezing and thawing of soil moisture is a process which needs special consideration. The main cause of soil creep in this area is the freezing and thawing of soil moisture. The effect of soil moisture changes are only slight even when the summer period is considered alone. Both the angle of slope and the vegetation cover have an effect on the rate of soil creep but the relative importance of these is difficult to judge since one type of measurement indicated the importance of the percentage of bare area and another type suggested that the angle of slope was most significant. The lack of relation between movement and other soil characteristics is thought to be due to the fact that soil moisture has little effect in causing creep.

The rate of scree movement at two sites (given by the geometric mean) was 14.3 and 31.0 cm/yr. These rates compare well with measurements made in South Georgia by Smith (1960), are less than a rate for some Lake District screes given by Caine (1963) and much greater than a rate from Swedish Lappland reported by Rudberg (1964). The most important cause of movement is the freezing and thawing of interstitial moisture. Two different types of movement were found; creep (probably caused by freezing and thawing) and rolling or sliding of individual particles (for which no cause could be established). The movement of particles is reflected in the fabric pattern of scree material, which shows a pole aligned on the slope direction and an upslope imbrication. The strength of this preference is as strong or stronger than that noted in previous studies of scree fabric.

The rate of erosion caused by slow mass movements is much smaller than that of debris flows. Soil creep and slope wash occur at similar volumetric rates but slope wash is probably more important in terms of rates of erosion. The rates of processes are comparable to those measured in Northern Sweden but are much smaller than those of the Upper Rhine. The total rate of deposition since the deglaciation of this area is about 20 times that of the measured processes. This discrepancy can be attributed to either the lack of information on the present processes or to a variation of erosion rates since deglaciation, or both. The second of these is considered more important since the processes not measured would have had little effect on the volume of the fan for which the deposition rate was calculated.

RECOMMENDATIONS FOR FURTHER WORK

This study has demonstrated the value of different techniques in investigating mass movement processes. Some methods were shown to be of little value over a short time scale. The ¾ inch PVC tubing was too rigid while Young Pits with pins for markers did not reflect the movement occurring. The inclinometer used also proved to be unsatisfactory. Approaches that gave good results were the use of ¼ inch PVC tubing (for rates of soil creep) and T-bars (for the causes of soil creep). However the use of different lengths of T-bars was not justified by the results in that no systematic variation of amounts of movement with length of T-bar was found. A larger number of sites with fewer T-bars (but of the same length) would probably have given more interesting results.

Although the investigation of causes demonstrated the importance of freezing and thawing of the soil moisture, some movement did occur in summer and a slight tendency for correlation with soil moisture changes existed. This relation could be more successfully evaluated if a more direct method of obtaining a continuous soil moisture record was used. The importance of the short-term "cyclic" component of creep (Kirkby, 1965), is not known and should be evaluated.

An analysis of the errors involved in calculation of erosion rates showed that the most important source of error was sampling. Hence, improvements in the estimate of erosion rates would probably result from more objective site selection and a greater number of sites, probably balanced by fewer instruments at each site.

On a more general scale, many processes were omitted from this study and this necessarily limits the value of estimates of the overall rate of erosion. Especially important is the rate of denudation caused by removal of salts in solution shown by other workers to be very important. Also, only passing consideration was given to the relation between the present forms and rates of processes. Although an understanding of the processes themselves is important, it is only part of the primary aim of geomorphology, the explanation of landforms. Much more data on both a spatial and a temporal scale is required before this can be even partly achieved in this area.

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LIST OF APPENDICES

APPENDIX I ANALYSIS OF REGOLITH

FOLK PARAMETERS

After the combining the cumulative graphs from the dry sieving and hydrometer analysis the 5, 16, 26, 50, 75, 84, and 95 percentiles were read off in ϕ units. This data was then transferred to punched cards and the Folk Parameters computed on the University of Canterbury's IBM 1620. The four parameters used are described below.

Graphic Mean Size (M_z)

This gives a measure of the overall size and is defined by:

$$M_z\ (\phi) = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

Inclusive Graphic Standard Deviation (δ_I)

This parameter is a measure of sorting and is given by:

$$\delta_I(\phi) = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

Folk suggests the following verbal classification for $\delta_I\ (\phi)$:

< 0.35	very well sorted
0.35-0.5	well sorted
0.5 -0.7	moderately well sorted
0.7 -1.0	moderately sorted
1.0 -2.0	poorly sorted
2.0 -4.0	very poorly sorted
> 4.0	extremely poorly sorted.

Inclusive Graphic Skewness (Sk_I)

The degree and "sign" of assymetry is indicated by this parameter which is defined by:

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 5}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi)}$$

The following verbal classes are suggested:

+1.0 to +0.3	strongly fine-skewed
+0.3 to +0.1	fine-skewed
+0.1 to -0.1	near symmetrical
-0.1 to -0.3	coarse-skewed
-0.3 to -1.0	strongly coarse-skewed.

Graphic Kurtosis (K_G)

This parameter is a measure of the ratio of the sorting in the "tails" of the curve and the sorting in the central portion, and is given by the formula:

$$K_G = \frac{\phi 95 - \phi 5}{2.44\ (\phi 75 - \phi 25)}$$

The verbal limits for this measure are:

$<$ 0.67	very platykurtic
0.67-0.90	platykurtic
0.90-1.11	mesokurtic
1.11-1.50	leptokurtic
1.50-3.00	very leptokurtic
$>$ 3.00	extremely leptokurtic

ATTERBERG LIMITS

Liquid Limit

The Casagrande liquid limit device was used in the determination of the liquid limit. A sample of about 200 gm and worked into a smooth paste after all small stones were removed. Part of the sample was placed in the cup of the liquid limit device and a groove cut with a special grooving tool. The handle of the device was rotated until the groove came together for ½ inch at the bottom. The moisture content of the sample was then determined by weighing and oven-drying. This process was repeated for more portions of the original sample with increasing amounts of moisture. The moisture content of the portions of the sample were then plotted against the logarithm of the corresponding number of blows. After a line was fitted to this plot the moisture content corresponding to 25 blows was read off and this was taken as the liquid limit.

Plastic Limit

A small pellet of soil was rolled on a dry smooth glass surface into a thread of ⅛ inch diameter. This was continued until the thread broke into crumbs ⅛ to ½ inch long. This was taken as the plastic limit. Several determinations were made for each sample and averaged.

Shrinkage Limit

The volume and weight of a small pat of soil was recorded at frequent intervals during oven-drying. Moisture content was then plotted against volume/dry weight of the soil. The shrinkage limit was then determined from this graph as the moisture content at which no further decrease in volume occurred.

APPENDIX II METHODS OF STATISTICAL ANALYSIS

CORRELATION AND REGRESSION

Methods of correlation and regression analysis are discussed by Ezekiel & Fox (1966).

For simple two-variable relations the best fit line

$$Y = a + bX$$

is derived from the following equations:

$$b = \frac{N\Sigma XY - (\Sigma X)(\Sigma Y)}{N\Sigma X^2 - (\Sigma X)^2}$$

$$a = \frac{\Sigma Y - b\Sigma X}{N}$$

where: Y = dependent variable

X = independent variable

N = number of observations

The b-value in this equation indicates the amount of change in Y for every difference of one unit in X.

Pearson's product-moment correlation coefficient (r) was used to express the degree of relation of the two variables. This is given by the formula:

$$r = \frac{N\Sigma XY - (\Sigma Y)(\Sigma X)}{\sqrt{\left[N\Sigma X^2 - (\Sigma X)^2\right]\left[N\Sigma Y^2 - (\Sigma Y)^2\right]}}$$

This can have a range of values from +1.0 to -1.0 with +1.0 indicating a perfect direct correlation and -1.0 a perfect inverse correlation. To test the significance of this value a t-test given by Gregory (1963, p.180) was used:

$$t = \frac{r\sqrt{N - 2}}{\sqrt{1 - r^2}}$$

Multiple correlation and regression were also used and this analysis was done on the IBM 1620 using a regression programme written by M. Mathieson.

ANALYSIS OF VARIANCE

This was used to test the significance of difference of site characteristics. The same model is used throughout. The sites were taken in pairs with a null hypothesis of no difference between them. The sums of squares for between variation and within variation were derived and divided by their respective degrees of freedom* to give the between and within mean squares. Division of the between by the within mean squares gave the F-value and the significance of this was read from a table of the F distribution using the appropriate degrees of freedom (Krumbein & Graybill, 1966, p.422). The null hypothesis of no difference was accepted or rejected according to significance reached.

* Degrees of freedom for the between sum of squares are $k-1$.

Degrees of freedom for the within sum of squares are $N-k$,

where: N = total number of cases

k = number of classes.

APPENDIX III FABRIC ANALYSIS

TWO-DIMENSIONAL ANALYSIS

The method used in two-dimensional fabric analysis was that outlined by Curray (1956). For the orientation and inclination of particles in each sample the following measures were obtained:

Vector mean($\bar{\theta}$) - a measure of central tendency of the distribution,

Vector magnitude (R) - a measure comparable to the standard deviation.

These are defined in the formulae:

$$\bar{\theta} = \tfrac{1}{2} \arctan \frac{\Sigma n \sin 2\theta}{\Sigma n \cos 2\theta} \qquad \text{(degrees)}$$

$$R = \frac{\sqrt{(\Sigma n \sin 2\theta)^2 + (\Sigma n \cos 2\theta)^2}}{\Sigma n} \times 100 \qquad (\%)$$

where θ = azimuth of each observation.

The significance of R was tested (using a Rayleigh test) against a random distribution, and against a uniform distribution using a χ^2 test.

THREE-DIMENSIONAL VECTOR ANALYSIS

The method used in three-dimensional vector analysis is an extension of the method discussed above with the advantage that orientation and inclination of particles are considered together. The analysis was done using a computer programme developed by Andrews & Shimizu (1966). This programme gave the vector magnitude (R) and the mean orientation and dip. The hypotheses that the distribution was random was tested using the equation:

$$R = \sqrt{NX^2}$$

For N equal to 50 the value of R should be above 11.39 at 0.05 level (Andrews & Shimizu, 1966, p.156). Other output from the programme includes Fisher's estimate of precision (k), which indicates whether the distribution is spherical normal, and the spherical radius of confidence around the mean vector.

APPENDIX IV FOLK PARAMETERS

MEAN SIZE (M_z) (Ø units)

Site	1	2	3	4
Sample				
0-10 cm				
A	-1.13	-1.66	2.63	0.23
B	-1.66	-0.86	-2.73	1.20
C	-2.76	-0.96	-0.80	1.16
10-20 cm				
A	-1.00	00.40	0.16	0.20
B	-4.36	00.60	-3.16	0.90
C	-2.73	1.30	-3.16	1.06
20-30 cm				
A	0.40	0.13	-2.40	0.90
B	-4.36	-0.33	-4.40	1.06
C		1.26	-4.23	0.43

INCLUSIVE GRAPHIC STANDARD DEVIATION (σ_I)

Site	1	2	3	4
Sample				
0-10 cm				
A	-2.56	-2.73	-3.99	-2.94
B	-2.78	-3.28	-2.40	-2.77
C	-1.88	-2.49	-3.63	-2.96
10-20 cm				
A	-3.14	-3.35	-3.78	-3.35
B	-1.69	-2.70	-1.49	-2.62
C	-1.78	-2.81	-2.75	-2.75
20-30 cm				
A	-3.23	-3.20	-3.28	-3.18
B	-1.51	-3.30	-1.46	-3.13
C		-3.41	-1.74	-2.84

INCLUSIVE GRAPHIC SKEWNESS (Sk_I)

Site	1	2	3	4
Sample				
0-10 cm				
A	-0.37	-0.40	-0.19	-0.15
B	-0.37	-0.05	-0.58	-0.42
C	-0.46	-0.32	-0.51	-0.04
10-20 cm				
A	-0.57	-0.07	-0.01	-0.13
B	-0.50	-0.14	-0.30	-0.40
C	-0.42	0.21	-0.73	-0.16
20-30 cm				
A	-0.07	-0.08	-0.78	-0.28
B	-0.55	-0.14	-0.68	-0.15
C		-0.12	-0.59	-0.15

GRAPHIC KURTOSIS (K_G)

Site	1	2	3	4
Sample				
0-10 cm				
A	1.18	0.81	0.91	1.25
B	0.94	0.69	1.71	1.03
C	1.75	0.87	0.73	1.04
10-20 cm				
A	0.87	0.86	0.67	1.37
B	2.62	0.82	2.28	1.20
C	1.63	0.97	0.52	1.09
20-30 cm				
A	0.74	0.86	0.95	1.38
B	3.43	0.72	1.72	1.10
C		0.86	1.38	1.32

APPENDIX V COMPUTATION OF ERRORS

ACCUMULATION OF MEASUREMENT ERRORS

The maximum relative error involved in multiplying a number of individual measurements (for which the measurement error can be estimated) can be obtained by summing the individual errors as shown by the following derivation:

$\left|\frac{\Delta x}{X}\right|$ is the relative error in variable x.

For $x = uv$

$$\log x = \log u + \log v$$

Differentiating gives:

$$\frac{\Delta x}{x} = \frac{\Delta u}{u} + \frac{\Delta v}{v}$$

so that the maximum relative error in x is given by:

$$\left|\frac{\Delta x}{x}\right| = \left|\frac{\Delta u}{u}\right| + \left|\frac{\Delta v}{v}\right|$$

SAMPLING ERROR

The standard error of the mean is given by the estimated standard deviation of the items in the universe divided by the square root of the number of cases in the sample:

$$S_{Mx} = \frac{\bar{S}_x}{\sqrt{n}} = \frac{S_x\sqrt{\frac{n}{n-1}}}{\sqrt{n}}$$

where: S_{Mx} = standard error of the mean of x

$\bar{S}_x$ = estimated standard deviation of the universe

S_x = standard deviation of the sample

n = number of observations

For the volumetric soil creep results S_{Mx} = 0.6954

At the 0.05 level the error with a sample of 14 is $2.2 S_{S_M}$ *

This represents an error of 45.8%.

* Ezekiel & Fox (1966, p.22, Table 2.3).

APPENDIX VI VOLUME OF THE ALLUVIAL FAN

Cross-sections of the alluvial fan and the valley side (from Lake Sarah to the top of Sugarloaf) were superimposed and vertical line drawn from their point of intersection to a base line level with the bottom of the fan. The volume of the fan was given by the 69^{o} segment of the cone on the alluvial fan cross-section minus the same segment on the valley-side cross-section. The volume of a cone is given by the formula:

$$V = 1/3 \pi r^2 h$$

where: V = volume

r = radius of cone

h = height of cone

The alluvial fan section gave:

$$V = \frac{\pi}{3} x (883.9)^2 \times (121.9) \times \frac{69}{360}$$

$$= 19,119,950.1 \text{ m}^3$$

The valley section volume was given as:

$$V = \frac{\pi}{3} \times (493.1)^2 \times (121.9) \times \frac{69}{360}$$

$$= 5,949,186.7 \text{ m}^3$$

The volume of the alluvial fan was then given as:

$$\underline{13,170,763.4 \text{ m}^3}$$

This figure may underestimate the actual volume since the valley-side slope was assumed to be unaltered.